PULSED OPERATION OF A HIGH-POWER
AMPLIFIER WITH COMPLEX LOAD IMPEDANCE

Dunham Laboratory
Yale University
New Haven, Connecticut

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Preface

This report is the fourth concerned with research accomplished in connection with Navy Contract N onr - 433(00), between Dunham Laboratory, Yale University, and the Office of Naval Research, Department of the Navy. The problem considered in the research is that of the operation of vacuum-tube power amplifiers with complex load impedances. In the preceding reports, the use of triodes, tetrodes, and pentodes in such amplifiers was considered from a theoretical viewpoint. In the accompanying report is given a description of experimental work on a high-power pulsed amplifier taken from a naval sonar system.

The research was carried on by J. G. Skalnik and W. J. Cunningham; the report was written by the undersigned.

W. J. Cunningham

New Haven, September, 1953

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List of Symbols

$a_1 = (E_{c2}/\mu_{12})/e_1$

$a_2 = E_{c1}/(E_{c2}/\mu_{12})$

e_b instantaneous plate voltage

e_{bm} minimum value of e_b (only symbol for which m signifies a minimum)

E_{bb} d-c plate supply voltage

e_{c1} instantaneous control-grid voltage

e_{cm} maximum positive value of e_{c1}

$-E_{c1}$ d-c control-grid supply voltage

e_{c2} instantaneous screen-grid voltage

E_{c2} d-c screen-grid supply voltage

e_{c3} instantaneous suppressor-grid voltage

e_g a-c component of e_{c1}

E_g maximum amplitude of e_g

e_p a-c component of e_b

E_p maximum amplitude of e_p

e_1 reference voltage for normalization

f frequency of operation

G' equivalent perveance, applying to plate current only

i_b instantaneous plate current

i_{bm} maximum value of i_b

i_{c1} instantaneous control-grid current

i_{cm} maximum value of i_{c1}

I_{g1} maximum amplitude of fundamental component of i_{c1}

I_{p1} maximum amplitude of fundamental component of i_b

i_s total instantaneous space current

i_{sm} maximum value of i_s

i_1 reference current for normalization

P_b a-c power in plate-circuit load

t time

Z_b magnitude of plate load impedance

α_p angle of plate current flow

β exponent in equation for i_b

θ angle of plate load impedance

μ_{12} control-grid-to-screen-grid amplification factor

μ_{1p} control-grid-to-plate amplification factor

ϕ angle between e_g and $-e_p$

Abstract

In several reports issued previously, a theoretical analysis has been given for the steady-state operation of a vacuum-tube power amplifier with a complex load impedance. This theoretical work was checked experimentally with amplifiers operating in the steady state at low power levels. One application of an amplifier which sometimes must operate with a complex load impedance is in naval sonar equipment. Such a sonar amplifier produces short pulses of high-frequency energy at power levels that are quite high. In the accompanying report is given a description of tests made using the amplifier from a Type XQHB sonar system. Experimental measurements were made on the amplifier and compared with characteristics of the operation predicted from the theoretical analysis. Agreement between experiment and prediction is moderately good. Reasons for disagreement include the difficulty of experimental measurement with pulsed operation, and the fact that the assumptions used in the theory are satisfied only reasonably well by the amplifier.

I. Introduction

In some kinds of equipment, it is desirable to obtain electrical energy in the form of short pulses of alternating current. Characteristically, the frequency of the current is high enough that many cycles of the carrier take place within the envelope of a single pulse. Typical pulses occur separated by appreciable time intervals, so that the duty factor[@] is a number much less than unity. Under such conditions of operation, the peak power developed during the pulse is many times the average power measured over an interval including several pulses. The temperature rise of components having usual physical dimensions depends upon the power dissipated in them over relatively long time intervals. Thus, the operating temperature of equipment generating pulses of the sort just described depends upon the powers averaged over appreciable time, and these averages are only a fraction of the peak powers developed during the pulse. Therefore, equipment generating energy as pulses with small duty factor can be composed of components much more compact than would be required for steady-state operation at the power level of the pulse.

There is, of course, a build-up and decay at the beginning and end of each pulse, and these represent transient types of operation. During the pulse itself, however, there usually are many cycles of the oscillation, and the operation is essentially a steady-state type. An analysis based on steady-state operation should be applicable during the interval of the pulse. Associated with the beginning and end of the pulse, however, may be new phenomena that do not appear in steady-state analyses.

[@] Approximately,

$$\text{duty factor} = \frac{\text{pulse duration}}{\text{interval between pulses}}$$

Vacuum-tube amplifiers, designed for Class-C operation, are commonly used in certain systems for generating pulses of high-frequency energy. The use of electronic equipment allows the properties of the pulse to be controlled rather easily and with considerable flexibility. Furthermore, large power can be obtained with components that physically are not too bulky. Power amplifiers of this kind perform most efficiently when the load into which they operate is a pure resistance. Unfortunately, certain applications sometimes require that the load impedance be complex. An extensive theoretical analysis of the operation of vacuum-tube power amplifiers with complex load impedances has been carried out.[1] This analysis is based on a number of assumptions needed to simplify a problem that inherently is quite complex. These assumptions include, first, that the a-c plate and grid voltages of the amplifier tube are sinusoidal functions of time. This assumption implicitly involves the additional assumption of steady-state operation. Further, it is assumed that the static characteristic curves for the tube can be represented by simple algebraic equiations. This assumption rules out several phenomena that may occur in an actual tube, such as secondary emission and cathode saturation, and limits operation to frequencies low enough that transit-time effects are negligible. Finally, the d-c resistance of the load impedance of the amplifier is assumed to be negligible.

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1. W. J. Cunningham and J. G. Skalnik,

Report No. 1, Triode power amplifiers with complex load impedances, April, 1952

Report No. 2, Power amplifiers using pentodes or beam tetrodes with complex load impedances, August, 1952

Report No. 3, Design procedures for vacuum-tube power amplifiers with complex load impedances, October, 1952

Contract N onr - 433(00), Dunham Laboratory, Yale University

The results of this analysis are presented in two forms. One form is a collection of equations from which calculations can be made applying to any desired situation. Another form is a family of design charts plotted with normalized coordinates. Once certain parameters applying to any chosen tube are determined, these design charts can be used to allow a quick estimate of the operation of that tube as an amplifier in a wide range of conditions.

II. Application of Analysis to Pulsed Amplifiers

The steady-state analysis of a power amplifier applies to triode, beam tetrode, or pentode tubes. Pulsed amplifiers commonly operate with a d-c plate supply voltage that is quite high. It is desirable that the d-c and a-c voltages necessary at the control grid of the tube be as low as possible. The control grids of tetrodes or pentodes can operate at relatively lower voltages than those of triodes, and thus triodes are less suitable for use in pulsed amplifiers. Only tetrodes and pentodes are considered in the present discussion of pulsed amplifiers.

In most respects, the analysis of a Class-C amplifier operating in the steady state is applicable to its operation as a pulsed amplifier, so long as many cycles of the oscillation occur during the pulse. There are a few differences in the operation of the pulsed amplifier that are worth consideration, however. Some of these differences are fundamental to the type of operation, and some are properties peculiar to the apparatus used in the two kinds of amplifiers. Among the differences are the following.

1. An assumption basic to the steady-state analysis is that the static characteristic curves of the amplifier tube can be described by simple algebraic equations. This assumption applies fairly well for

many tubes commonly used in steady-state amplifiers. It applies rather less well to some tubes designed for pulsed amplifiers. An example of the difference is shown in the curves of Figs. 1 and 2, taken from manufacturer's data[2] and applying to Type 814 and 715-C tubes respectively. The Type 814 is a beam pentode with 50 watts rated plate dissipation, normally used in steady-state operation. The Type 715-C is a tetrode with 60 watts rated plate dissipation, designed for pulsed operation.

The equations used in the analysis to represent the static curves for a tetrode or pentode neglect the effect of plate voltage upon plate current. It is evident from Fig. 1 that this assumption holds fairly well for the Type 814 tube, so long as the plate voltage is greater than about half the screen voltage. From Fig. 2, however, it is seen that the assumption is rather poor for the Type 715-C tube, where the plate current changes more rapidly with plate voltage. The knee of a plate-current curve for the Type 715-C is more rounded and occurs at a relatively higher plate voltage than for the Type 814. There is an additional effect not apparent in the curves shown. The negative control-grid voltage needed to give plate-current cutoff in the Type 715-C is abnormally large. This corresponds to a considerable reduction in the control-grid-to-screen-grid amplification factor, μ_{12}, in the neighborhood of cutoff. The analysis, based on the independence of plate current and plate voltage, and the constancy of factor μ_{12}, is less accurate when applied to an amplifier employing a tube such as the Type 715-C.

2. The design of an amplifier operating in the steady state is usually such that the plate, and perhaps the grids, of the tube

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2. RCA Tube Handbook, HB-3, (Radio Corporation of America, Harrison, New Jersey).

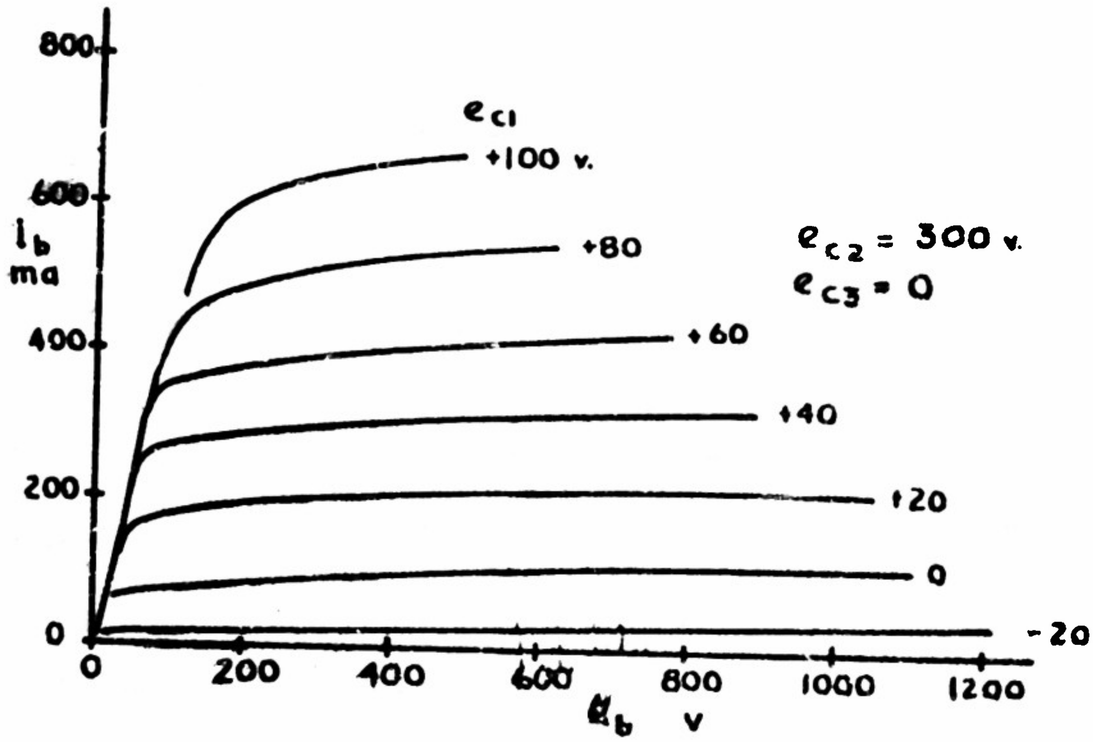

Fig. 1. Static curves for Type 814 tube

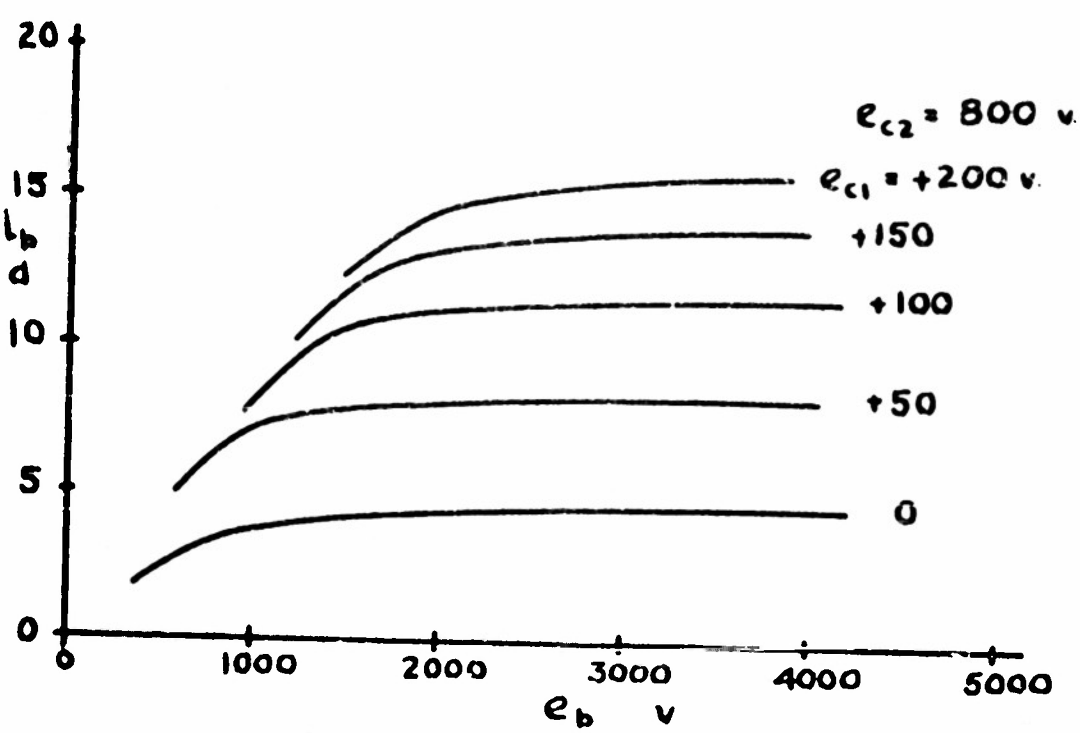

Fig. 2. Static curves for Type 715-C tube

dissipate the maximum amount of power. This maximum power is specified by the manufacturer of the tube so that the temperature rise of the electrodes will not be too large. Other limiting factors in the design may be set by maximum specified voltages or currents, but usually power dissipation is the ultimate limitation.

Often a pulsed amplifier is operated with a duty factor that is small enough that power dissipation in the electrodes of the tube is not the ultimate limitation. Instead, the peak voltages allowable before insulation breaks down, or the peak currents that can be supplied safely by the cathode, become the real limitation. Whether it is the average power, or the voltages and currents, that control the design depends upon how large the duty factor may become. If the power proves to be unimportant, the design procedure given in the analysis (Ref. 1) must be modified.

3. Tubes are usually operated in steady-state amplifiers so that the peak cathode-current density is held to a conservatively small value. During a cycle of the operation there is no serious difficulty in obtaining the required instantaneous current. In pulsed amplifiers, however, the peak cathode-current density often is allowed to become so large that it is obtained only with real difficulty. If this is the case, the current may fluctuate erratically and unpredictably near its peak value, and the phenomenon of cathode fatigue[3] may appear. None of these effects are considered in a simple analysis of the amplifier.

4. In a Class-C amplifier operating in the steady-state, plate current flows for less than half each cycle of the carrier wave. Thus, the plate current is a sequence of pulses having a shape dependent upon

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3. G. N. Glasoe and J. V. Lebacqz, Pulse generators, (McGraw-Hill, New York, 1948), Ch. 3.

the exact operating conditions. The flow of these pulses through the plate load impedance gives rise to the a-c plate voltage. This voltage is assumed to be a sinusoidal function of time. Evidently a sinusoidal voltage at the fundamental frequency of the carrier will be obtained only if the impedance of the plate load is relatively high at this frequency, and relatively low at all harmonics of this frequency, as well as at zero frequency. A tuned load having a reasonably high circuit Q is indicated.

Somewhat conflicting requirements on the plate load impedance appear if the amplifier is pulsed. During the pulse itself, essentially steady-state operation takes place and the filtering provided by a high-Q load is desirable. The transient effects at the beginning and end of the pulse may lead to difficulties, however. Exactly what does occur[6] depends upon how rapidly the envelope of the pulse rises and falls, whether the load is tuned to the frequency of the carrier within the pulse envelope, and what the Q of the load is. If the carrier frequency differs slightly from the frequency to which the load is tuned, and if the pulse envelope rises abruptly, a kind of ringing may occur in the envelope of the voltage existing across the load. The resulting overshoot in the envelope leads to the appearance of excessive voltages across the load, and these may cause unexpected breakdowns. Such irregularities in the pulse envelope are prevented by limiting both the Q of the load impedance and the rate of rise of the pulse envelope.

5. Rectifier systems are commonly used to provide sources of direct current for the amplifier. Power is supplied to the rectifier at the usual low power-line frequencies. In steady-state operation,

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[6] See Appendix A.

conditions are such that the rectifier operates at a constant rate and supplies the same current during each cycle of conduction.

For pulsed operation, the currents required by the amplifier during the pulse are many times those that can be supplied by the rectifier, as it is usually designed. Thus, the rectifier must supply energy to a large capacitor for storage during an appreciable interval, and this stored energy is utilized by the amplifier during the pulse. As a result of this design, the d-c voltages applied to the amplifier tube characteristically drop considerably during the interval of the pulse. This voltage change is not considered in the analysis of the steady-state amplifier.

III. Experimental Pulsed Amplifier

One of the applications of [illegible] vacuum-tube amplifiers, operated so as to produce pulses, is in certain types of naval sonar systems. In such systems a pulse of high-frequency sound energy is produced by a suitable electromechanical transducer supplied with a pulse of electrical energy. The electrical pulse is obtained from a vacuum-tube amplifier. The load to which the amplifier must supply power consists of a matching transformer coupling the amplifier to the transducer. The electrical impedance of this combination is a complicated function of frequency. The transducer often consists of a large number of components, each tuned mechanically and electrically. These components are connected in parallel, possibly with additional elements added for overall tuning. The electrical impedance presented to the amplifier by this load is almost certain to have several maxima at different frequencies.

In order that the electromechanical transducer operate most effectively, it should be supplied with energy at its frequency of mechanical resonance, and this ideally should be the operating frequency for the system. For most efficient operation of a Class-C amplifier, its load impedance should be a resistance with zero phase angle. Thus, the electrical tuning in the circuit should be adjusted to make the impedance presented to the amplifier tube a resistance at the operating frequency. These criteria govern the normal adjustment of the sonar amplifier and its load.

Under some conditions of use, the operating frequency of the sonar system must be changed. Because of the large number of components involved, it is impractical to attempt readjustment of the tuning of the load circuit. At the new frequency, the impedance presented to the amplifier is no longer resistive, but acquires a phase angle different from zero. The efficiency of the amplifier thereby is reduced.

In order to study experimentally the operation of such an amplifier working with a variety of load impedances, the driver amplifier of a Type XQHB sonar system was obtained.[*] The Type XQHB system was designed initially almost ten years ago, but the circuits are typical of more recent equipment.

The circuit for the final stages of the amplifier is shown in Fig. 3. The last stage employs two Type 5D21 (or their equivalent, Type 715-B) tubes connected in parallel. These tubes operate with a high value of d-c plate voltage, and with d-c control-grid and screen-grid voltages chosen to insure plate-current cutoff during periods of no pulse. When a pulse of energy is to be produced, a large a-c voltage is applied to the control grids, causing the tubes to function as Class-C amplifiers. This grid voltage is supplied by a driver amplifier, also employing a Type 5D21 tube operated Class-C.

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[*] This amplifier was one of several similar units supplied as a loan to Dunham Laboratory by the U. S. Navy Underwater Sound Laboratory, at the request of the Office of Naval Research.

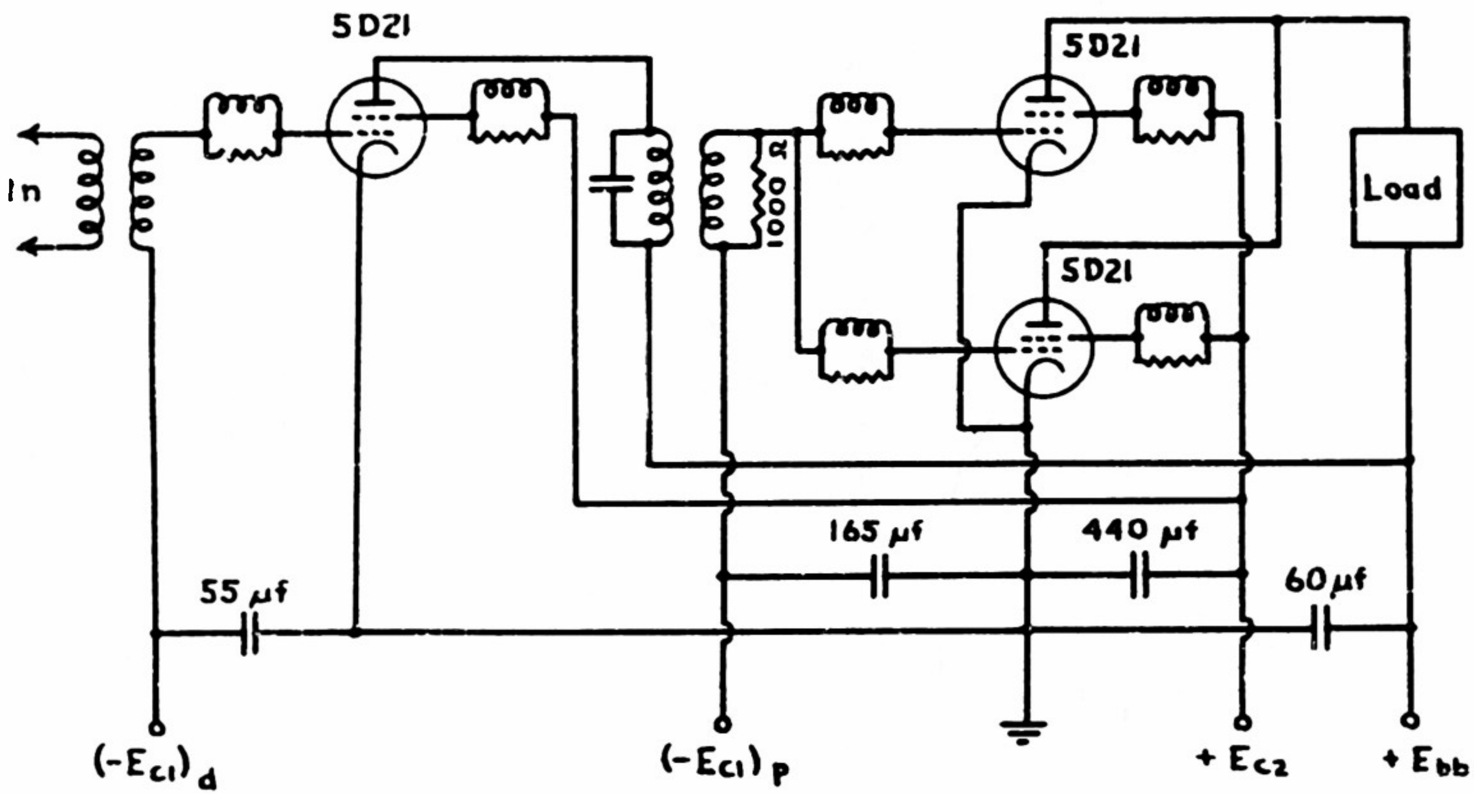

Fig. 3. Driver and power amplifier from Type XQHB Sonar.

The d-c voltages for all the tubes are obtained from rectifier circuits operated from the 60-cps power line. These power supplies make use of transformers and rectifier tubes so small that they cannot provide the large currents necessary during a pulse. Therefore, large capacitors must be used in each power supply circuit to store energy during the periods between pulses, and to provide the burst of energy needed for the pulse. These capacitors are shown in Fig. 3, but the remaining parts of the power supplies are not shown.

In order to prevent the occurrence of parasitic oscillations of high frequency, small r-f choke coils and resistors are inserted in all of the control-grid and screen-grid leads.

An a-c pulse must be provided at the input terminals of the driver amplifier. A rather complicated circuit is used in the Type XQHB sonar to supply this signal. In the interests of simplicity, experimental work on the Type XQHB was carried out using a separate source for this pulse signal. The pulse-generating and voltage-amplifier circuits of a Type PRO sonar system were used.[⊕] A block diagram of the resulting combination is shown in Fig. 4. The circuits for the driver amplifier and power amplifier of Fig. 4 are those shown in Fig. 3. The circuits of Fig. 4, preceding the driver amplifier, include an oscillator which is controlled by a pulse-generating circuit. When this circuit is keyed, the oscillator produces an a-c pulse at the frequency desired for the carrier. Following the oscillator is a voltage amplifier and a gain control. The amplitude, carrier frequency, and pulse duration of the signal supplied to the driver amplifier can be adjusted simply.

[⊕] This equipment was among the items supplied by the Underwater Sound Laboratory.

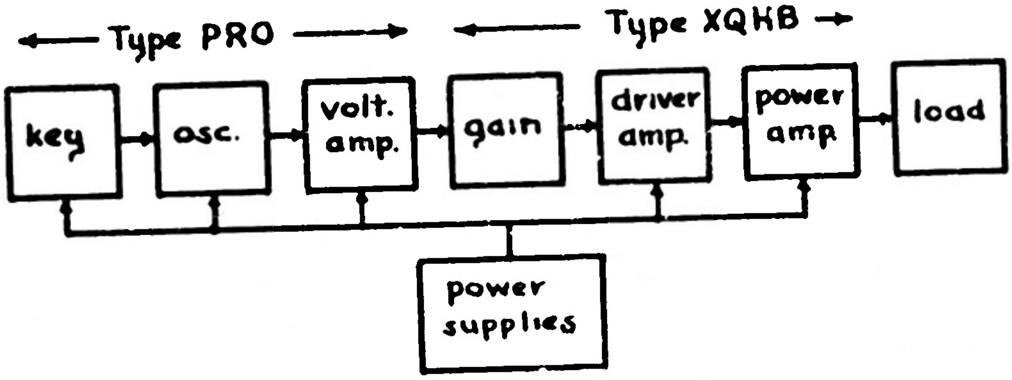

Fig. 4. Components of experimental system.

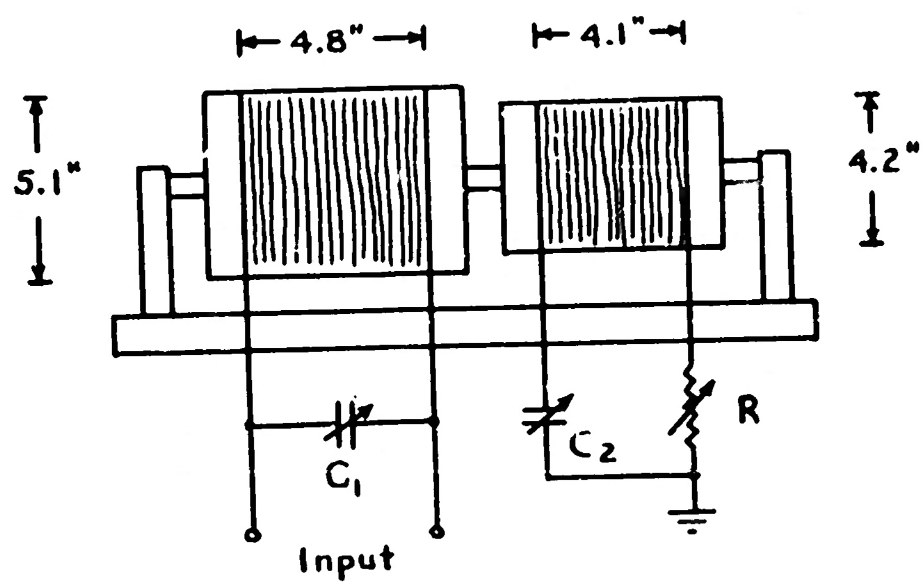

Fig. 5. Adjustable-impedance load circuit

The power amplifier of the Type XQHB made use of a tightly-coupled air-core transformer for matching the amplifier tubes to the transducer. In the experimental work, it was desirable to have a load impedance that could be varied within fairly wide limits, both in magnitude and in angle. Some preliminary impedance measurements indicated that the original transformer did not lend itself to such wide variations in impedance as were desired. The fixed tight coupling between primary and secondary of the transformer prevented adequate adjustment of the impedance. A different kind of load circuit was implied.

The load circuit that was used in the experimental work consists of a double-tuned air-core transformer, with adjustable coupling between the windings. Its configuration is shown in Fig. 5. The primary and secondary coils are wound with number 18 wire on fiber tubes of the dimensions shown. The primary contains 57 turns and the secondary contains 50 turns, both coils having the spacing between adjacent turns controlled to give the winding lengths shown. The secondary is arranged to slide coaxially into the primary, with an arbitrary scale divided into inches serving to identify their relative positions. Capacitors C_1 and C_2 and resistance R, all adjustable in steps, together with the continuously-adjustable coupling, allow the input impedance of the load circuit to be controlled over a wide range. Care was taken in the construction to use components which would withstand the high peak voltages and currents existing in the load during the pulse from the amplifier.

The operating frequency for the system was chosen to be 29 kilocycles. At this frequency, the impedance presented at the input terminals of the load is shown in Fig. 6. These curves are plotted from data obtained by experimental measurements. There are four regions of Fig. 6,

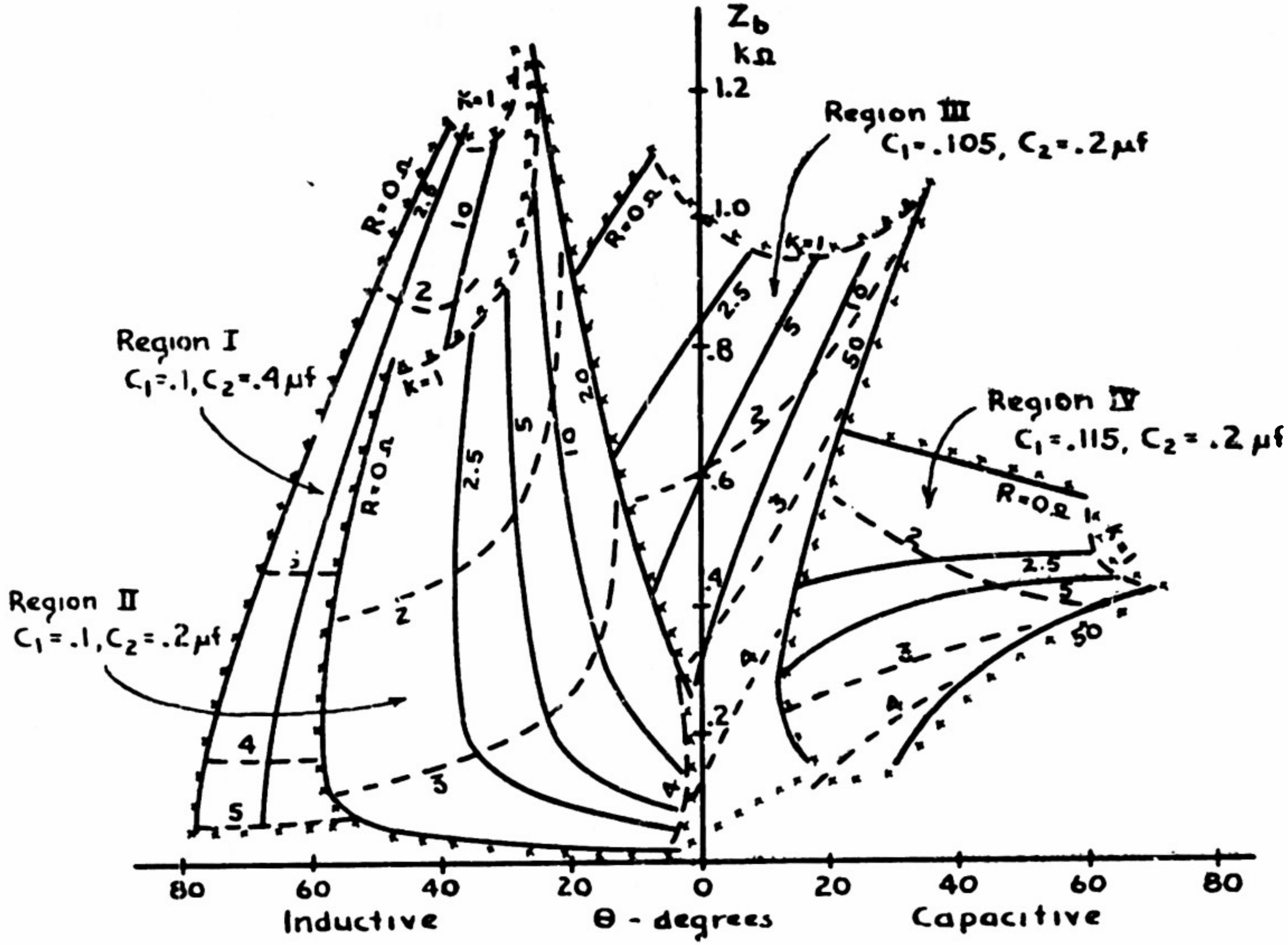

Fig. 6. Adjustment of load for specified impedances at f = 29 kc.

with values of capacitances C_1 and C_2 being constant in any one region. Within a given region, control of the load impedance is achieved by simultaneous adjustment of resistance R and of the coupling. The coupling as indicated on the scale of inches is given the symbol K in Fig. 6.

Typical curves showing the variation of the magnitude of impedance with frequency for three adjustments of the load are shown in Fig. 7. Each adjustment gives the magnitude of 500 ohms at the frequency of 29 kilocycles. One adjustment gives an angle of zero; the others give angles of 45 and 60 degrees, inductive impedance, at this frequency. The parameters for the 45 degree angle do not happen to be those given in Fig. 6, but are an alternate combination. The curves of Fig. 7 show that the impedance is large in magnitude near the operating frequency of 29 kilocycles. The curves continue to fall smoothly as frequency rises, so that the impedance is small at harmonics of the carrier frequency. This condition is necessary in order that the a-c voltage across the load be nearly sinusoidal when it is used in the Class-C amplifier.

The two peaks on the curve for the 45-degree angle at 29 kilocycles are typical of an over-coupled double-tuned system with small damping in each circuit. In preliminary tests an attempt was made to use the original transformer of the Type XQHB to give impedances of this sort. It was found that the coupling of this transformer was so tight that the double peaks were widely separated in frequency. As a result, the impedance was not small at harmonics of the carrier frequency, and the a-c plate voltage of the amplifier would not be sinusoidal.

Since the amplifier is operated in pulsed fashion, it is necessary to use oscilloscopes for measuring the various voltages existing in

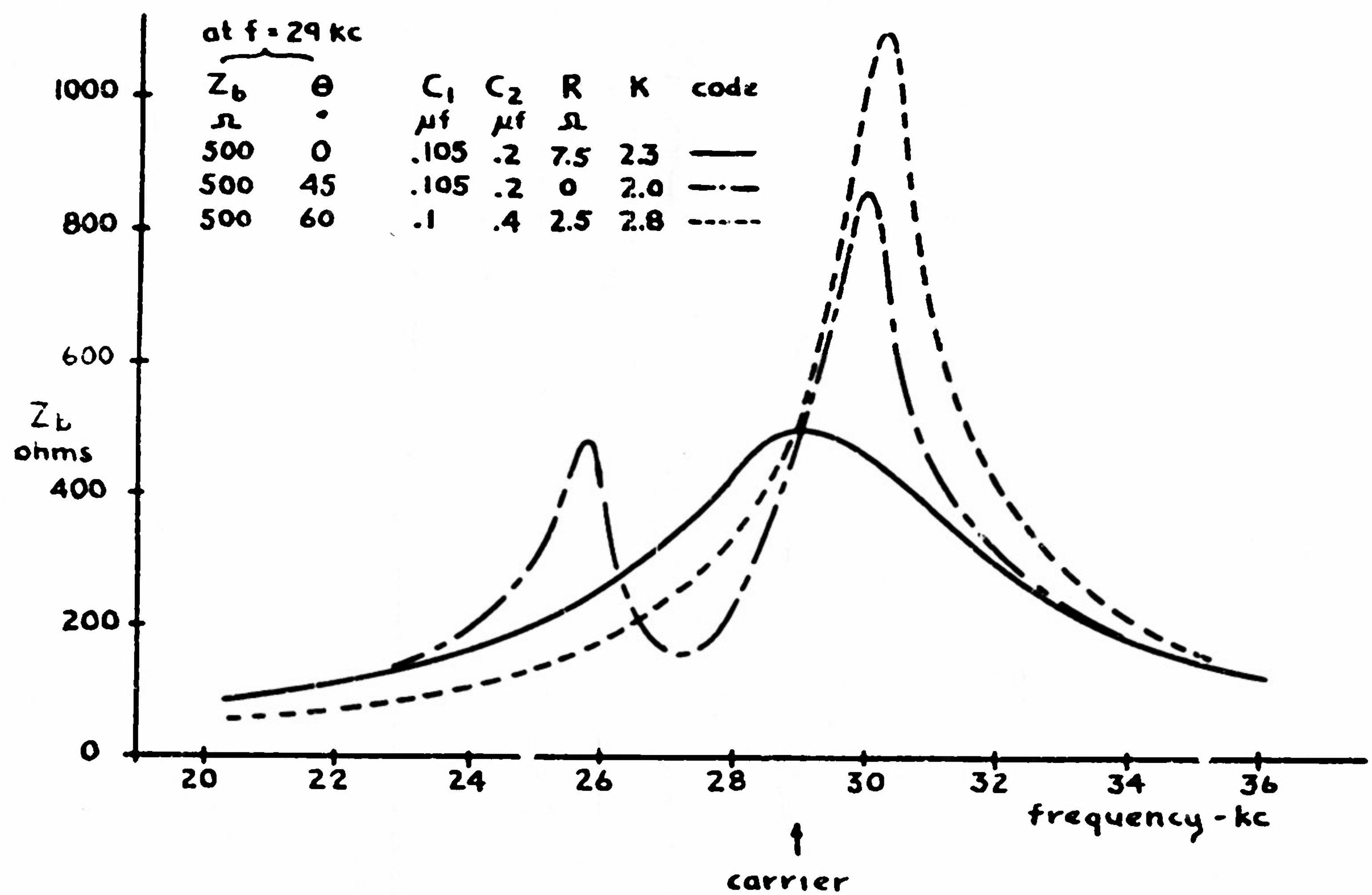

Fig. 7. Impedance vs. frequency for certain adjustments of load.

the system during a pulse. Calibrated voltage dividers at the control grid and plate of the power amplifier tubes serve to reduce the a-c voltages at these points to values small enough to be applied to an oscilloscope. A small resistor in the cathode circuit of the tubes allows the cathode current to be measured. The oscilloscopes operate with a single sweep for horizontal deflection. The sweep is triggered from the keying circuit of the oscillator.

IV. Experimental Observations

According to the circuit diagram accompanying the Type XQHB system, the d-c plate voltage for the power amplifier is supposed to be 4200 volts. In the particular unit that was used for the experiments, this voltage could not be raised so high. A choice of $E_{bb} = 3000$ volts was made arbitrarily for all experimental measurements. This voltage could be adjusted by means of a control in the power supply. The lower voltage reduces the maximum power output which can be obtained, approximately in the ratio of the squares of the voltages. The d-c screen-grid and control-grid voltages could not be adjusted easily. Their values were as follows, screen-grid voltage $E_{c2} = 380$ volts, control-grid voltage for the driver amplifier $(E_{c1})_d = 220$ volts, and control-grid voltage for the power amplifier $(E_{c1})_p = 320$ volts. These grid voltages agree well with values specified for them.

In normal operation, the duration of the pulse produced by the Type XQHB is in the order of thirty milliseconds. This duration is long enough, and the currents needed by the amplifier are high enough, that all the d-c voltages drop by large fractional amounts during the pulse. Furthermore, the Type 5D21 tubes used in the power amplifier were designed for radar pulse generators operating with pulses in the order of one microsecond duration. The pulse duration of the Type XQHB is 30,000 times as long. If a pulse duration less than normal is used, the change in d-c voltages is reduced and the tubes are worked less severely. For this reason, all experimental data were taken with a pulse duration of about three, rather than thirty, milliseconds.

The keying system is such as to produce a pulse envelope at the input to the driver amplifier which changes smoothly and has rounded corners. The tuned transformer in the plate circuit of the driver was found to have so little dissipation that the decay of the pulse was prolonged by a continuing transient oscillation. In order to prevent this extension of the pulse envelope, a resistor 1000 ohms in value was added across the secondary of this transformer. With the extra resistor, the pulse envelope at the grid of the power amplifier is essentially the same as at the grid of the driver amplifier.

The carrier frequency during a pulse was held constant at 29 kilocycles. This is a typical frequency of operation for sonar systems. The fixed tuning of the plate transformer of the driver amplifier was adjusted to this frequency.

The special load circuit was used as the plate load impedance for the power amplifier. Through the use of the curves of Fig. 6, this load circuit could be adjusted to give a wide range of real or complex impedances of known value.

Experimental data were taken for the power amplifier operating under the conditions described. The gain control was used to adjust the a-c grid voltage of the power amplifier to a desired value. The plate load impedance then was varied and measurements were made of the a-c plate voltage. The measurements were taken to the peaks of the voltage pulses on the oscilloscope figures. All the voltage dividers and oscilloscopes were calibrated to allow the trace on the screen to be interpreted directly in volts.

Reproductions of oscillograms showing typical waveforms in the amplifier are shown in Figs. 8-11. These figures were made by photographing the screen of the oscilloscope. The resulting photograph was then enlarged, traced in ink, and axes added. The individual cycles of the high-frequency carrier were visible within the pulse envelope of the original photograph, but no attempt was made to reproduce them in the tracing.

In Fig. 8 is shown the high-frequency pulse at the grid of the power amplifier. This oscillogram was made with the gain control set at its maximum value. The corresponding pulse across the load impedance of the power amplifier is shown in Fig. 9. In both cases, the load impedance was Z_b = 500 ohms in magnitude, and $\theta = 0$ in angle at the carrier frequency. The envelope of the pulse changes relatively smoothly.

In Fig. 10 the time scale is expanded so an individual cycle of the grid voltage of Fig. 8 can be seen. The distortion present as the grid becomes positive and grid current flows is apparent. For lower values of a-c grid voltage, less distortion occurs. An individual cycle of the space current is shown in Fig. 11. This pulse is asymmetrical, since the distortion of the grid voltage has caused it to be asymmetrical. Because of filtering action of the plate load impedance of the power amplifier, individual cycles of the plate voltage are essentially sinusoidal in shape, and they are not shown.

All the numerical measurements of voltage and current are obtained with some difficulty. Observations must be made during the relatively brief pulse. None of the voltages remain constant during the pulse. The d-c voltages change because of the inability of the power supplies to furnish the necessary large currents. The a-c grid voltage changes

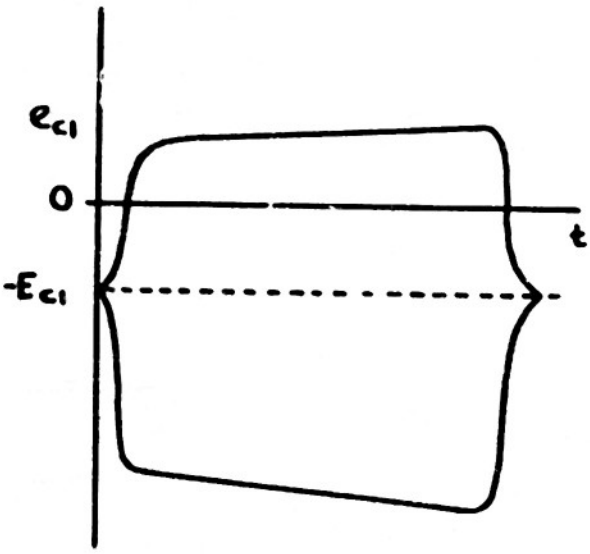

Fig. 8. Grid-voltage pulse

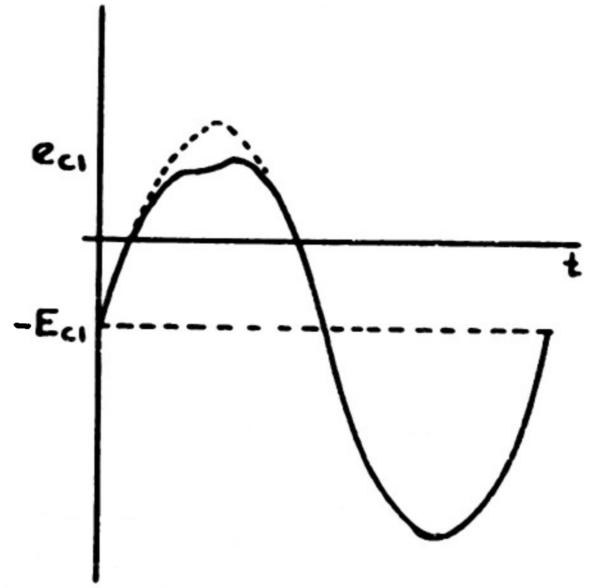

Fig. 10. Cycle of grid voltage

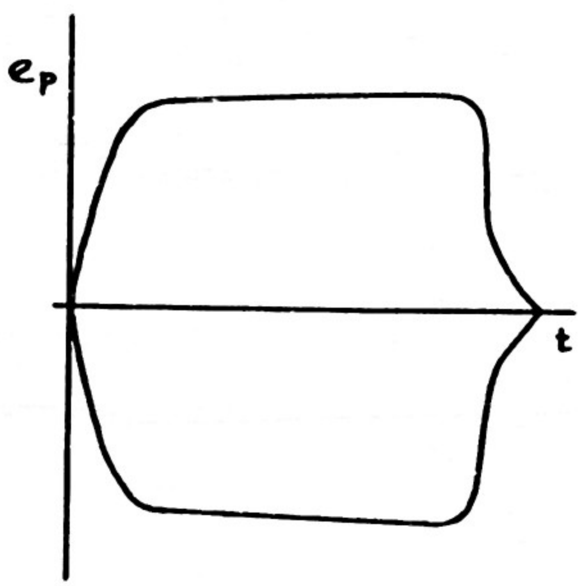

Fig. 9. Pulse across plate load.

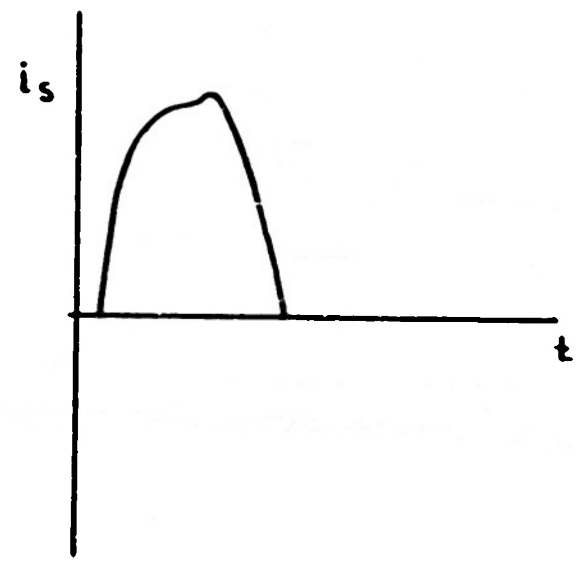

Fig. 11. Cycle of space current

In all cases, $E_{bb} = 3000$v, $E_{c1} = 320$v, $E_{c2} = 380$ volts.
$Z_b = 500\ \Omega$, $\theta = 0$

because it is influenced by loading due to the flow of grid current, and this is a function of the changing d-c voltages. The grid current depends upon how positive the grid becomes. This depends, in turn, upon a small difference between a-c and d-c grid voltages, both of which are large. As a result of these various considerations, all voltage measurements involve considerable error. Experimental data shown in the curves which follow represent averages of a number of observations, and are intended to be the best possible estimates regarding the operation.

In Fig. 12 is plotted a series of data obtained with the angle of the load impedance zero, so that the load is a pure resistance R_b. The parameter for the curves is the peak a-c control-grid voltage, E_g. The maximum positive instantaneous grid voltage, e_{cm}, can be found as

$$e_{cm} = E_g - E_{c1} = E_g - 320 \text{ volts.}$$

The top curve of Fig. 12 applies when the gain control is at its maximum setting. The a-c grid voltage is quite distorted from a sinusoidal waveform at this maximum setting, as evident in Fig. 10, and it is rather meaningless to specify a value for E_g. For lower settings of the gain control, the voltage is a reasonably good sinusoid.

The power supplied to the load during the pulse can be found as

$$P_b = E_p^2/2R_b.$$

Since both E_p and R_b are given in Fig. 12, power can be calculated. Curves of power are plotted in Fig. 13, calculated from the data of Fig. 12. In Fig. 14 are plotted the same data as in Figs. 12 and 13, but using different axes. Here, contours of constant P_b and Z_b are shown, plotted as solid lines.

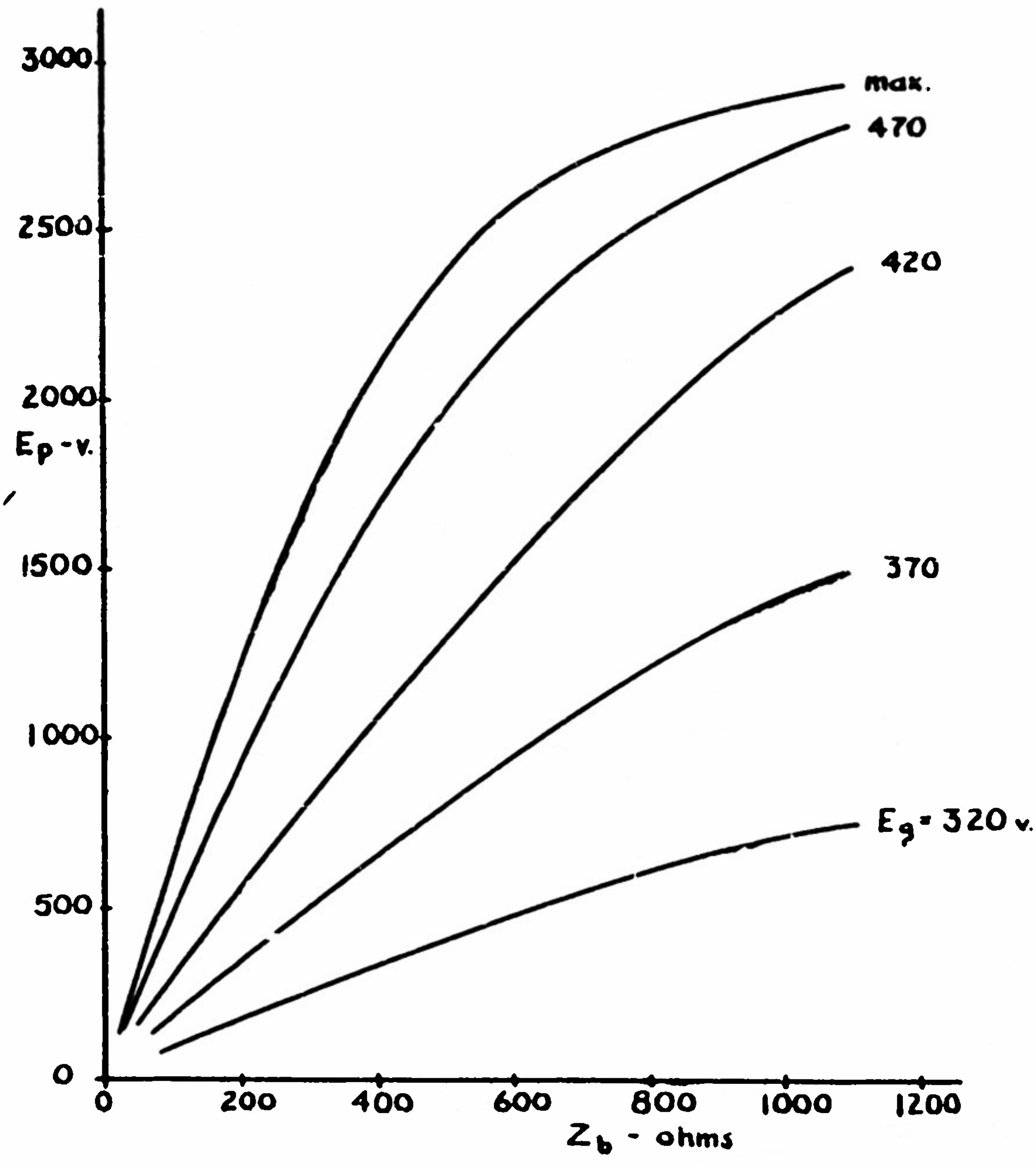

Fig. 12. Experimental data. $E_{bb} = 3000$ v, $E_{c2} = 380$ v.
$E_{c1} = 320$ v, $\theta = 0$

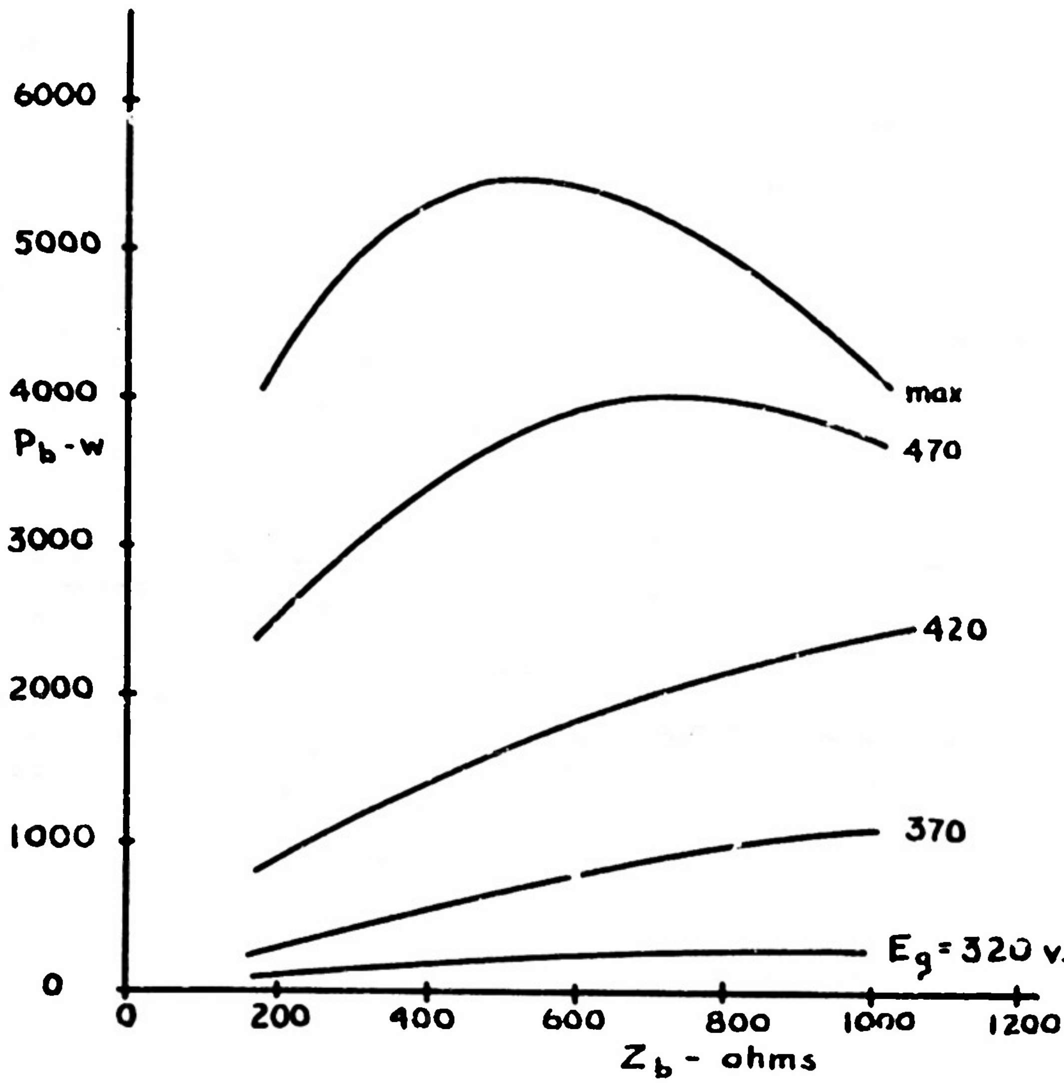

Fig. 13. Experimental data E_{bb} = 3000 v, E_{c2} = 380 v.
E_{c1} = 320 v, θ = 0

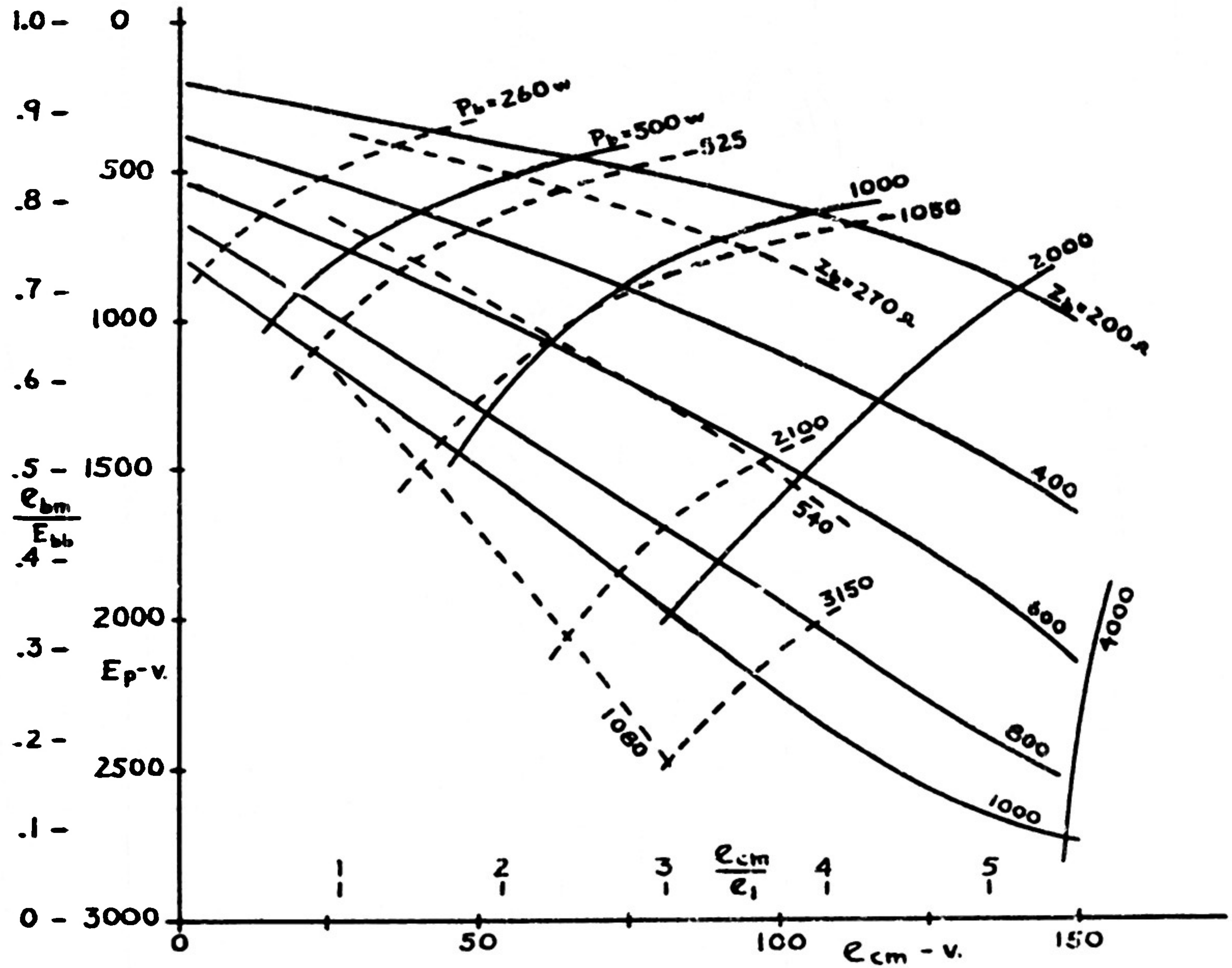

Fig. 14. Operation of amplifier. Solid curves measured, E_{bb}=3000, E_{c2}=380, E_{c1}=320, θ=0.
Dotted curves predicted, e_1=27v, I_1= .7a (2 tubes), β=1.3

The peak value of the fundamental component of plate current, I_{p1}, can be found as

$$I_{p1} = E_p/R_b.$$

Values of I_{p1}, calculated thus, are plotted in Fig. 15. The peak value of the total space current can be found from the peak voltage existing across a small resistor of known value in the cathode circuit. This peak current, i_{sm}, is plotted in Fig. 16. The space current, of course, is the sum of plate, screen-grid, and control-grid currents. The peak plate current, i_{bm}, is larger than I_{p1} by a factor depending upon the angle of plate-current flow, α_p, and the properties of the tube. Characteristically, this factor is between two and four. For conditions such that both E_g and E_p are large, currents to the grids also are large and i_{sm} is considerably larger than i_{bm}.

All data plotted in Figs. 12-16 were taken with the angle of the load impedance fixed at zero, and with variable magnitude of the impedance. In Fig. 17 are shown similar data obtained with a fixed magnitude for the load impedance, but with the angle allowed to vary. The magnitude was held constant at Z_b = 500 ohms, which is about the value giving maximum power output at the maximum available grid drive. From Fig. 17 it is apparent that both the a-c plate voltage E_p and the peak space current i_{sm} are essentially independent of the load angle θ, at least within the accuracy of measurement. Power supplied to the load can be found as

$$P_b = (E_p^2/2Z_b) \cos \theta$$

and is plotted also. Since E_p and Z_b do not change, P_b varies as $\cos \theta$.

Additional oscillograms of the envelope of the a-c voltage across the load impedance of the amplifier are shown in Fig. 18. In all cases, the magnitude was adjusted to give Z_b = 500 ohms, while three different

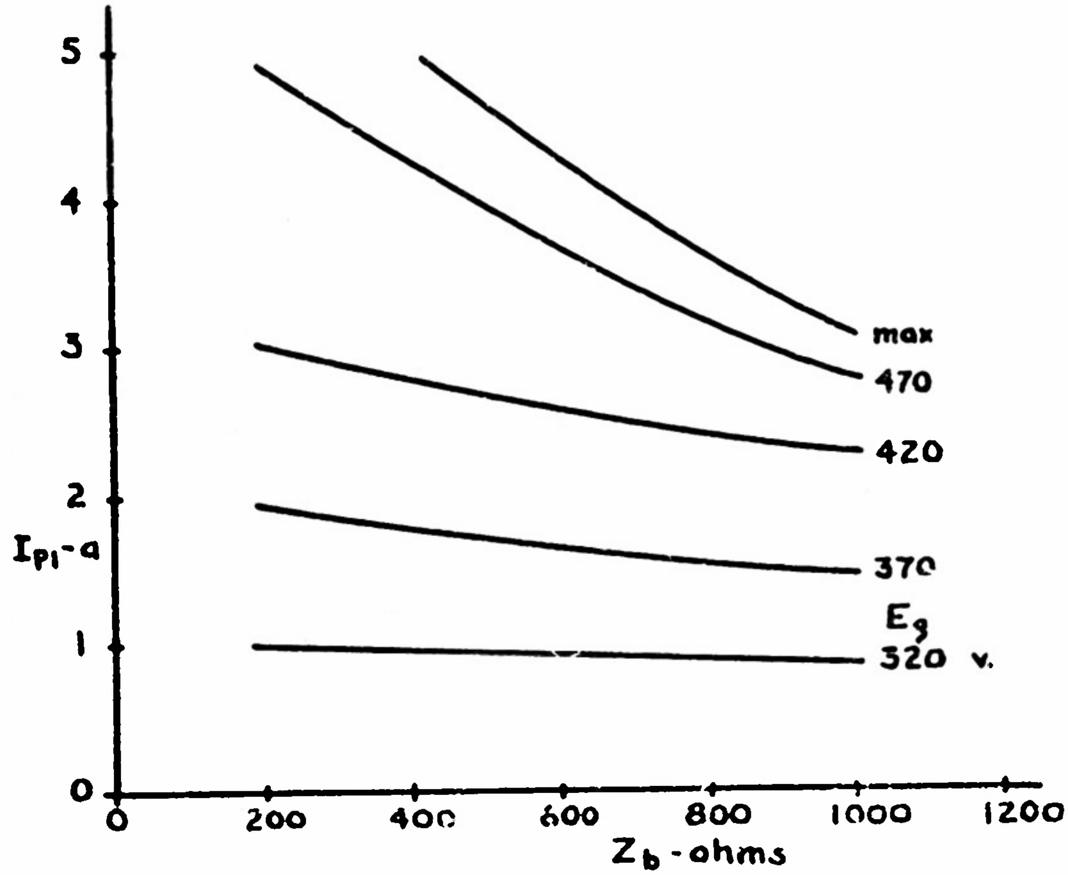

Fig. 15.

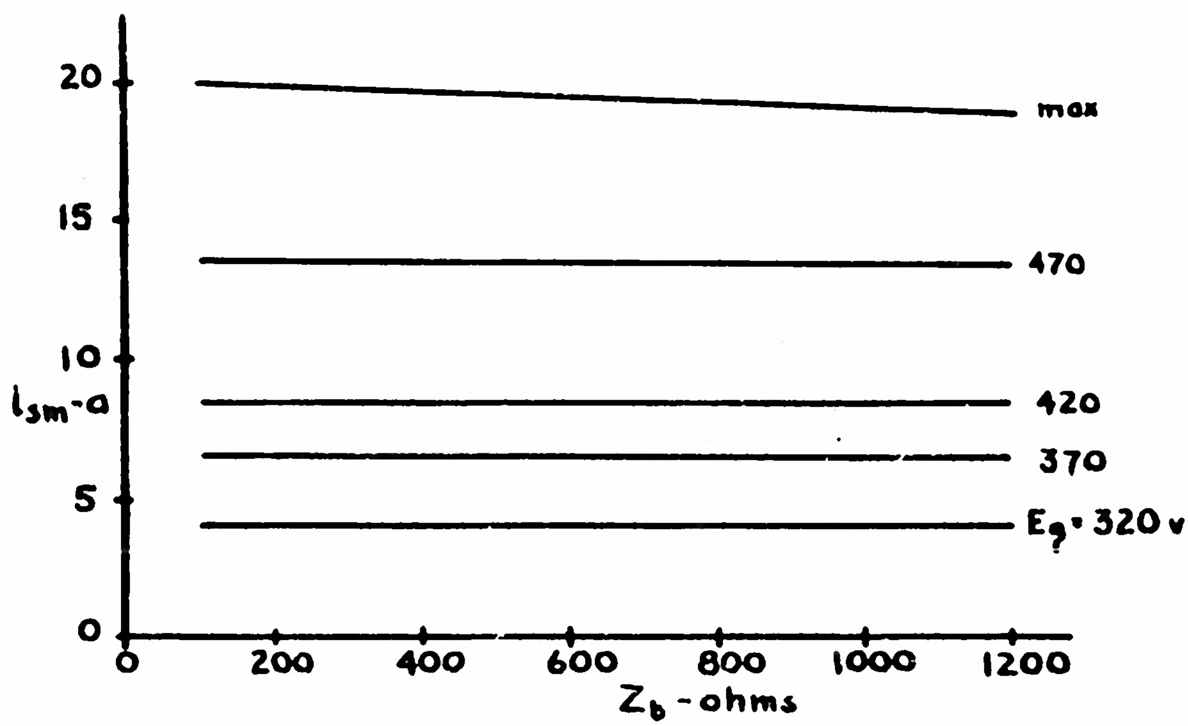

Fig. 16. Experimental data. E_{bb} = 3000 v, E_{c2} = 380 v, E_{c1} = 320 v, θ = 0

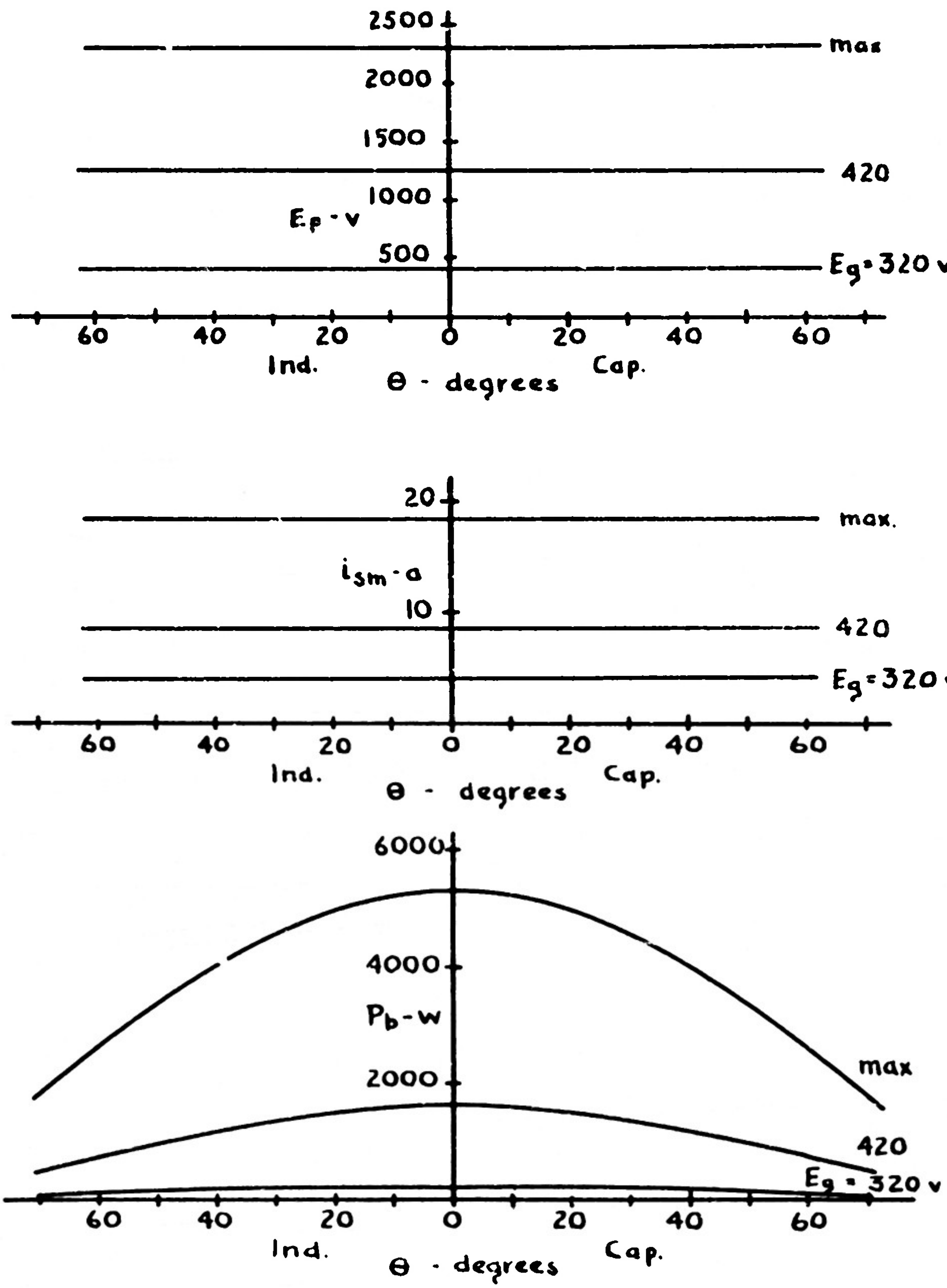

Fig. 17. Experimental data. $E_{bb} = 3000$ v, $E_{c2} = 380$ v,
$E_{c1} = 320$ v, $Z_b = 500$ Ω

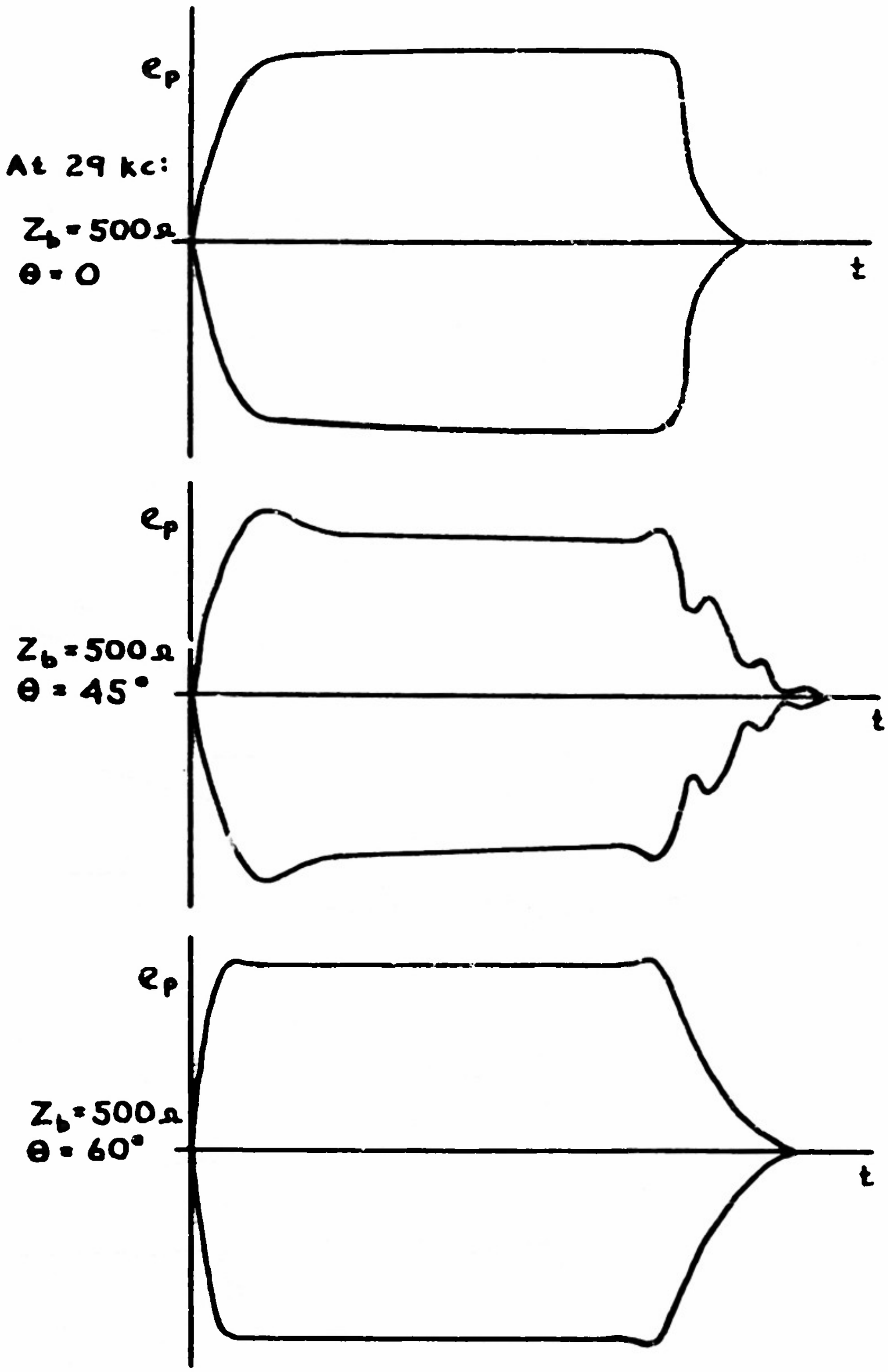

Fig. 18. Observed pulse envelopes across plate load. Load impedances as in Fig. 7.

angles were used, $\theta = 0$, 45, and 60 degrees, inductive, measured at the carrier frequency of 29 kilocycles. The magnitude of the load impedance as a function of frequency is plotted in Fig. 7. For the adjustments that give an angle different from zero, the impedance has a maximum at other than the carrier frequency of the pulse. As a result, transient oscillations occur at the beginning and end of the pulse, and the shape of its envelope is distorted.

V. Comparison of Analysis and Experiment

In the analysis (Ref. 1) of a Class-C amplifier a method is given for predicting the performance of the amplifier from static data for the tube. These static data must be available in order to apply the analysis. Currents and voltages existing in the tube of an amplifier operating in the steady state are relatively small. Static data concerning the tube with such small currents and voltages can be obtained with little difficulty by straightforward d-c measurement. Currents and voltages existing in the tube of an amplifier in pulsed operation are many times higher than those of the steady-state amplifier. Static data for such large currents and voltages cannot be obtained by simple d-c measurements without destroying the tube. As a result, pulse measurements are necessary to find the static data required to describe the pulsed amplifier. Equipment needed to obtain such pulsed data is rather similar to the equipment of the pulsed amplifier itself.

The amplifier of the Type XQHB sonar functions at high power with pulsed operation. Static data for the Type 5D21 tubes used as they are in the amplifier cannot be obtained by simple d-c measurements. These tubes were designed for radar pulse generators, working at very high voltages and short pulse durations. Several families of static characteristic curves for Type 715-C tubes (approximately equivalent to the

Type 5D21) are published by tube manufacturers, but the ranges that are covered are more applicable to a radar system than to the present sonar system. In particular, the screen-grid voltage used in the sonar amplifier is less than the values which appear in the published static data.

It is possible, of course, to extrapolate from published data and obtain an estimate of the static curves that should apply for some lower screen voltage. The result of such an extrapolation is shown in the dotted curves of Fig. 19. These curves represent an idealized estimate of curves which might apply to a single Type 715-C tube, operating with a screen-grid voltage $e_{c2} = 380$ volts. This is the screen-grid voltage existing in the experimental amplifier. In Fig. 1 it is assumed that the plate current is independent of plate voltage, so long as the plate voltage exceeds a value determined by the sloping line at the left of the figure. These estimated curves can be compared with the curves of Fig. 2, applying to the Type 715-C tube with $e_{c2} = 800$ volts.

In the analysis of the amplifier it is assumed that the plate current i_b of a tetrode (such as the Type 5D21) can be described by the equation

$$i_b = G'(e_{c1} + e_{c2}/\mu_{12})^{\beta}$$

where e_{c1} is the control-grid voltage, e_{c2} is the screen-grid voltage, G' is the perveance, μ_{12} is the control-grid-to-screen-grid amplification factor, and β is the exponent. A term e_b/μ_{1p} may also appear in the parenthesis of this equation, but usually it can be neglected. The three parameters G', μ_{12}, and β are determined from the static curves for the tube. The performance of a Class-C amplifier employing the tube is given in families of charts, of which Fig. 20 is a sample.*

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* This is the same as Fig. 10 of Report No. 2, Ref. 1.

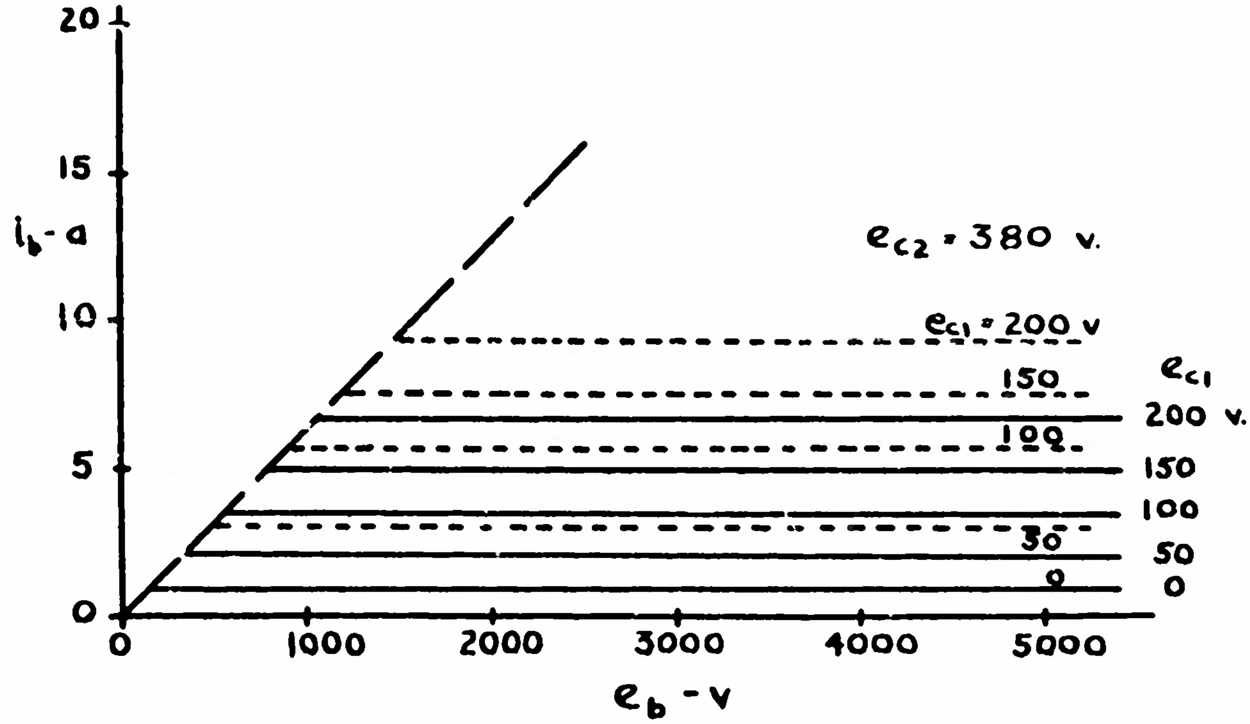

Fig. 19. Estimated static curves for Type 5D21 tube

—— from measurements on amplifier
---- from published data for Type 715-C

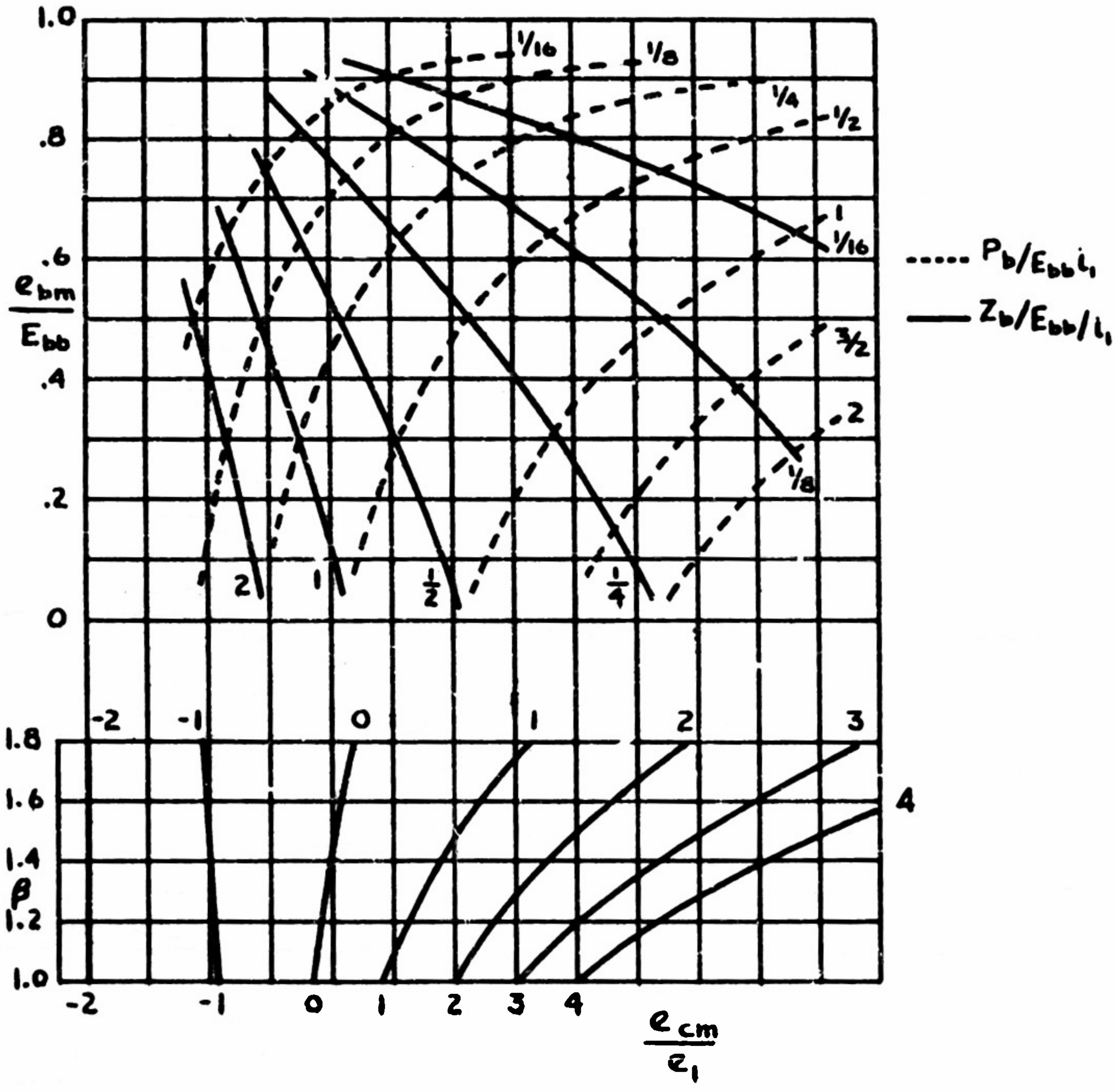

Fig. 20. Theoretical operating contours, $a_1 = 2$, $a_2 = 2$, $\theta = 0$

Additional parameters appearing on these charts are reference voltage e_1 and reference current i_1. Reference voltage e_1 is found as

$$e_1 = E_{c2}/(a_1\mu_{12}) = E_{c2}/2\mu_{12}.$$

Here E_{c2} is the d-c screen voltage of the amplifier, and a_1 is a constant given the numerical value, $a_1 = 2$, throughout the analysis. Reference current i_1 is found as

$$i_1 = G'(e_1)^{\beta}.$$

Voltage e_{bm} is the minimum instantaneous plate voltage during a cycle of the amplifier; voltage e_{cm} is the maximum positive instantaneous control-grid voltage; voltage E_{bb} is the d-c plate supply voltage.

The chart of Fig. 20 is but one of a family of such charts applying for different d-c control-grid bias voltages. This bias voltage is specified by a factor

$$a_2 = E_{c1}/(E_{c2}/\mu_{12}),$$

where E_{c1} is the bias voltage. In Fig. 20, $a_2 = 2$, corresponding to a bias voltage twice the cutoff value. The load impedance for Fig. 20 is assumed to be a pure resistance so that its angle is $\theta = 0$. The performance of an amplifier with parameters $a_2 = 2$ and $\theta = 0$ is described by Fig. 20. If the quantities β, e_1, i_1, and E_{bb} are specified for the amplifier, then the values of output power P_b and load impedance Z_b can be read from the figure for any chosen combination of voltages e_{bm} and e_{cm}.

The power amplifier of the Type XQHB has two Type 5D21 tubes with their elements connected in parallel. The value of the amplification factor, μ_{12}, for a Type 715-C tube can be estimated from the static curves for this tube, making use of the definition

$$\mu_{12} = -\Delta e_{c2}/\Delta e_{c1} \quad \text{for constant } i_b.$$

For median values of plate current, the value of μ_{12} is approximately $\mu_{12} = 7$, changing slowly with plate current. Near plate-current cutoff, however, μ_{12} drops abruptly and at cutoff its value is about $\mu_{12} = 2.5$. These numerical values are found making use of manufacturer's data with a screen voltage of 800 volts. The numerical value of μ_{12} should not change radically with screen voltage, however. It is assumed that these values of μ_{12} apply also to the Type 5D21 tubes, operated with a screen voltage of 380 volts.

The grid-bias voltage in the power amplifier is $E_{c1} = 320$ volts. Thus the value of parameter a_2 is

$$a_2 = E_{c1}/(E_{c2}/\mu_{12}) = 320/(380/2.5) = 2,$$

approximately. Since parameter a_2 is used in the analysis to specify cutoff conditions, the value of $\mu_{12} = 2.5$ applying near cutoff is used. The result, $a_2 = 2$, is the value of parameter a_2 for the chart of Fig. 20. Thus, Fig. 20 should be useful in describing the operation of the amplifier.

It should be possible to take the estimated (dotted) static curves of Fig. 19, and to determine from them values of quantities G' and β, and then to predict the operation of the actual amplifier from Fig. 20, observing that two tubes operate in parallel in the amplifier. When such a calculation is carried out, however, the agreement between observed data and predicted data is poor, particularly for large grid-driving voltages. Observed power output is consistently less than that predicted.

In order to try to locate the reason for this disagreement, a calculation was made in the reverse direction. Experimental data are plotted in Fig. 14 in a manner analogous to Fig. 20. Thus, it is possible to choose certain points on Fig. 14, and from these points to work back and find values of e_1, i_1, and β which will give better agreement with Fig. 20. When this is done, the resulting numerical values for a single tube are found to be

$$e_1 = 27 \text{ volts}$$

$$i_1 = 0.35 \text{ amperes}$$

$$\beta = 1.3 .$$

This value of e_1 is correct to fit the relation

$$e_1 = E_{c2}/2\mu_{12} = 380/(2)(7) = 27 \text{ volts}$$

as it should be. Here, the value of μ_{12} applying to median plate currents is used. The value of i_1 for two tubes in parallel, as in the amplifier, is twice that for a single tube.

If these numerical data are used with Fig. 20, predicted curves of P_b and Z_b can be found. Such curves are plotted as dotted lines in Fig. 14. The agreement between the observed and predicted curves of Fig. 14 is moderately good. The largest discrepancy occurs where the minimum instantaneous plate voltage is smallest. Where the plate voltage is small, the assumption that the plate current is independent of plate voltage is poor, as is evident from Figs. 2 and 19. At small plate voltage the plate current is smaller than expected, and the power output is reduced. This is the direction of the difference between the curves of Fig. 20.

The perveance G' needed to give the values of e_1 and i_1 used in the calculations can be found as

$$G' = i_1/(e_1)^{\beta} = 0.35/(27)^{1.3} = 0.005 \text{ amp/volt}^{\beta}$$

for a single tube. The resulting parameters, $G' = 0.005$ amp/volt$^{\beta}$, $\beta = 1.3$, and $\mu_{12} = 7$, can be used to predict static curves for the tube. A family of such curves is plotted as solid lines in Fig. 19.

It is evident that currents predicted from these curves are consistently smaller than those predicted from the curves obtained as extrapolated estimates from manufacturer's data. The two sets of curves would be brought into fair agreement if the value of G' were changed by about fifty percent.

a further check on the parameters of the tube, static data were obtained for a single Type 5D21 tube with all voltages scaled down sufficiently to allow simple d-c measurements without exceeding the power ratings for the tube. The results of these low-voltage measurements are shown in Fig. 21. The value for the control-grid-to-plate amplification factor, $\mu_{1p} = 220$, is large enough that the quantity e_b/μ_{1p} usually can be neglected without introducing serious error. The value for the control-grid-to-screen-grid amplification factor, $\mu_{12} = 4.5$, is reasonable. Values of μ_{12} estimated from manufacturer's data for the Type 715-C tube were $\mu_{12} = 7$ for plate currents of several amperes, and $\mu_{12} = 2.5$ at cutoff. The value of $\mu_{12} = 4.5$, for $i_b = 100$ milliamperes, is a mean of the other two values. The logarithmic plot of i_b and the quantity $(e_{c1} + e_{c2}/\mu_{12} + e_b/\mu_{1p})$ gives values of $\beta = 1.3$ and $G' = .0045$ amp/volt$^{\beta}$. These values agree well with those estimated from dynamic measurements on the power amplifier.

There is little reason to conclude that measurements at reduced voltages, such as these, are useful for finding parameters of the tube when operated at much higher voltages, for the agreement obtained here may well be fortuitous. However, the fact that agreement is obtained makes it seem likely that the manufacturer's data for the Type 715-C tube do not apply well to the Type 5D21 tubes actually present in the experimental amplifier.

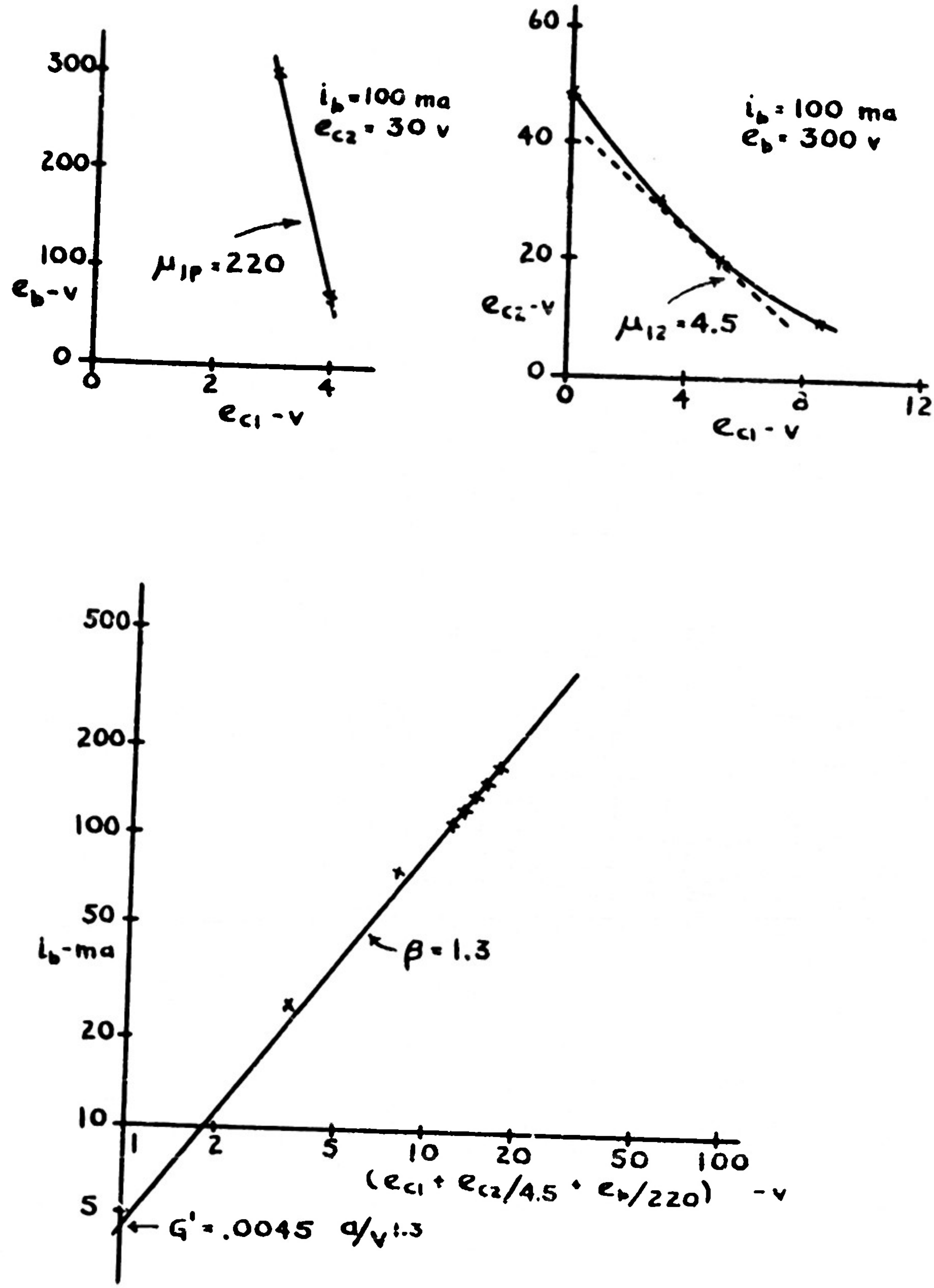

Fig. 21. Experimental static data for Type 5D21 tube

The conclusion may be drawn from all these measurements that a single Type 5D21 tube, as used in the power amplifier, can be described fairly well by the parameters, $G' = .005$ amp/volt$^{\beta}$, $\beta = 1.3$, and $\mu_{12} = 7$ for median currents. At cutoff, the value of μ_{12} drops to $\mu_{12} = 2.5$. With these parameters, the charts of the theoretical analysis, such as Fig. 20, can be used to predict the performance of the amplifier, with sufficient accuracy for design purposes.

Most of the preceding discussion has been concerned with the case of a load impedance that is a pure resistance with zero angle. Experimental data, such as those plotted in Fig. 17, indicate that the Type 5D21 tubes are a reasonably good approximation to the ideal tetrode. In other words, the plate current is almost independent of the plate voltage, and is determined by voltages at the control grid and screen grid. This statement holds so long as the instantaneous plate voltage never becomes too small. Since the grid voltages are not influenced by the plate load impedance, the plate current is independent of the load impedance. Thus, the effect of making the load impedance complex, with angle different from zero, is primarily to change the power developed in the load. If the magnitude of the load impedance is held constant, and the angle changed, power in the load varies as the cosine of the angle. Power changes only slowly near zero angle, but rapidly becomes smaller as the angle departs farther from zero.

In conclusion, it is well to observe again that there are a number of reasons why experimental data concerning the power amplifier are not in good agreement with data predicted from the theoretical analysis. Among the reasons for this discrepancy are the following.

1. Experimental data are obtained only with some difficulty. Because the duration of the pulse, during which time the amplifier

operates, is short, measurements must be made with the aid of oscilloscopes. Further, several seconds must elapse between pulses in order that d-c voltages return to the proper values. Numerical data taken from the trace of an oscilloscope have only limited accuracy. The figure on the screen is relatively small compared with the width of the trace and considerable error is involved in just the geometrical measurement. In addition, the calibration of all amplifiers and voltage dividers supplying the oscilloscope influences final numerical readings.

One of the most important quantities in describing the operation of a Class-C amplifier is the maximum positive instantaneous control-grid voltage, e_{cm}. This voltage cannot be measured directly, but must be found as the difference between the peak a-c grid voltage E_g, and the negative grid-bias voltage E_{c1}, thus

$$e_{cm} = E_g - E_{c1}.$$

However, both E_g and E_{c1} are relatively large quantities while e_{cm} is much smaller. Therefore, the error in finding e_{cm} is magnified with respect to the error in either E_g or E_{c1}.

Finally, because of uncontrollable variations in the system, no two pulses are exactly alike. This is especially noticeable for small values of e_{cm}. As a result it is difficult to get a set of quantitative data that is self consistent.

2. None of the d-c voltages supplied to the tubes remain constant during the interval of a pulse. The currents required by the amplifier during a pulse are so large that the small power supplies cannot deliver them. Instead, capacitors across the power supplies must discharge sufficiently to provide the necessary energy. Even though these capacitors have large values, all the voltages fall by amounts that are not insignificant during the duration of the pulse.

Still larger values of capacitance would reduce these drops in voltage, but increases of several times in the already large values would be needed to give any real improvement.

3. The a-c voltage at the grids of the amplifier tubes is not sinusoidal. This effect is shown in Fig. 10, which illustrates the flattening of the positive half cycle of the grid voltage. This figure applies to the case of the maximum a-c grid voltage obtainable with the equipment. Essentially the same effect occurs at lower voltages, but somewhat reduced in magnitude. The distortion in waveform comes about because of the very large current that flows in the control-grid circuit when the grid becomes positive. According to manufacturer's data, the grid current in one tube is about one ampere when the grid is 100 volts positive. For the two parallel tubes, the equivalent instantaneous resistance therefore is about 50 ohms. The internal output impedance of the driver must be less than this figure if distortion is not to occur. The combination of large a-c voltage and low impedance thus required of the driver could be achieved only by a driver amplifier of large power capabilities. Such a design is unreasonable. Therefore, a driver amplifier of practical design must be used, and the resulting waveform is distorted.

The operation of the amplifier is modified and the experimental measurement of the grid voltage is complicated when this voltage is not sinusoidal.

4. The a-c voltage at the plates of the amplifier tubes is not sinusoidal. This voltage is more nearly sinusoidal than is the grid voltage, however. The a-c plate voltage is developed across the load impedance by the action of the pulses of plate current in the load. The resulting voltage across the load will be sinusoidal only if the

impedance of the load is very large at the carrier frequency of the pulses, and very small at all harmonics of this frequency. Such is never the case in practice, and the plate voltage always is somewhat distorted.

In a tetrode, the plate current is relatively uninfluenced by plate voltage, so the operation of the amplifier is not changed greatly by a nonsinusoidal plate voltage. Measurement of this voltage is made inaccurate because of distortion, however.

5. It would be desirable to determine the plate current i_b in the experimental measurement. Because of the need to use an oscilloscope for measurement, only voltages can be observed. Thus, a current can be found only in terms of the voltage drop it produces across a small known resistance. In the experimental amplifier, the most suitable place to locate such a resistor is at the cathodes of the tubes. This location allows only the total space current i_s, rather than just the plate current, to be observed. The space current is larger than the plate current by the amount of the currents to control grid and screen grid. For positive control-grid voltage, these grid currents are comparable to the plate current.

6. The Type 5D21 tubes in the amplifier operate in such a way that the assumptions of the theoretical analysis apply to them only moderately well. In the analysis, the plate current is assumed to be independent of the plate voltage so long as the plate voltage is at least half the screen voltage.[*] As is evident from Fig. 2, this is not true for the Type 715-C tubes. Furthermore, it is assumed that the control-grid-to-screen-grid amplification factor μ_{12} is a constant. Again, for the tubes of the amplifier, this factor changes by a ratio

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[*] See Appendix B.

of almost three-to-one as the plate current increases from cutoff to a median value.

Because of these various differences which exist between conditions in the experimental amplifier and those assumed in the theoretical analysis, it is hardly surprising that agreement between sets of data obtained in the two ways is only moderately good.

VI. Comments on Amplifier Design and Operation

In a system such as the Type XQHB sonar, there usually is interest in obtaining as much power as possible from the amplifier. For this reason, the following comments are offered regarding the amplifier used in the experimental work.

The power actually supplied to the final output device, such as the transducer of a sonar system, is only a portion of the power developed by the amplifier. There is always loss of power in coupling circuits between the tubes and the output device. This loss of power can be minimized by proper design of the coupling circuits. Just how this can be done depends upon details of the system in question, and is not considered here. The problem of getting maximum power from the tubes is considered.

The power developed in the load is

$$P_b = (1/2)\ I_{p1}^{\ 2}\ Z_b \cos \theta$$

where I_{p1} is the fundamental component of plate current, and Z_b and θ are magnitude and angle of the load impedance. For a tetrode, such as the Type 5D21, the plate current is determined almost entirely by voltages on control grid and screen grid, so long as the a-c plate voltage is not too large. If the a-c plate voltage E_p becomes too large in comparison with the d-c plate supply voltage E_{bb}, so that the minimum instantaneous plate voltage

$$e_{bm} = E_{bb} - E_p$$

is too small, plate current is reduced by the low plate voltage. So long as e_{bm} is not too small, I_{pl} is essentially independent of the plate load impedance. Practically, if Z_b is made so large that E_p approaches E_{bb}, then I_{pl} drops. If Z_b is smaller, I_{pl} depends only upon control-grid and screen-grid voltages.

Output power will be increased if I_{pl} is increased, for a constant value of $Z_b \cos \theta$. The size of I_{pl} depends upon the peak plate current i_{bm} and the conduction angle α_p, increasing with both these quantities. The peak current is increased by raising either the d-c screen voltage E_{c2}, or the maximum positive instantaneous control-grid voltage,

$$e_{cm} = E_g - E_{c1}.$$

The plate-current conduction angle is given by

$$\alpha_p = 2 \cos^{-1} \left[\frac{E_{c1} - E_{c2}/\mu_{12}}{E_g} \right]$$

It is increased by increasing either E_{c2} or E_g, or by decreasing E_{c1}. Thus, the implication is that larger I_{pl} (and thus, power) will be obtained by raising either E_g or E_{c2}, and reducing E_{c1}.

There are several limitations here. If $Z_b \cos \theta$ is held constant, there will be no increase in a-c plate voltage, and thus in power, as soon as the product $I_{pl}Z_b$ approaches in value the d-c plate supply voltage E_{bb}. Further, if e_{cm} becomes too large, excessive control-grid current will flow. Such current must be supplied by the circuit driving the grid. Thus, the required driving power is increased. At the same time, the power dissipated at the grid is increased, and the rating of the tube may be exceeded.

In a pulsed amplifier, such as that of the sonar system, care must be taken to keep the tube cut off between pulses. Thus, an increase in E_{c2} must be accompanied by an increase in E_{c1}, rather than the decrease that would give larger α_p. Practically, in a pulsed amplifier, the ratio E_{c2}/E_{c1} must be held about constant. The voltage that has the greatest effect on I_{p1} is the voltage e_{cm}. An increase in e_{cm} increases the current I_{p1}, but at the expense of a rapid increase in driving power.

The d-c and a-c voltages in the amplifier of the Type XQHB seem to be well-chosen. An increase in voltage E_{c2} would give slightly increased I_{p1}, but a large change could not be expected. It would be necessary to raise E_{c1} and E_g along with E_{c2}, and any increase in power output would be accompanied by an increase in driving power. In addition, any increase in E_{c2} would require a considerable increase in the physical size of the components in the power supply providing this voltage.

An increase in E_g would increase I_{p1}, but with the necessity of increasing the driving power. The driver amplifier already employs a tube of the same type used in the power amplifier. It seems unreasonable to increase the size of the driver amplifier further. Moreover, any sizable increase in E_g will exceed the voltage ratings for the control grid of the Type 5D21 tube.

Probably the simplest way of increasing the power output from the amplifier would be to raise the d-c plate supply voltage E_{bb}. This voltage could be increased considerably and still not exceed the rating for the tubes. An increase in E_{bb} would not change current I_{p1} appreciably. However, it would allow the use of a higher value for Z_b and still not have voltage E_p approach too closely to E_{bb}. The maximum output power would increase approximately as the square of E_{bb}. An increase in E_{bb} would require physically larger components in the plate power supply.

A third tube could be added in parallel with the two tubes already in the power amplifier. This would necessitate an increase in the driving power, although the increase might be obtainable from the present driver amplifier with no change. The plate power supply also would have to be enlarged to allow for the extra current.

The two tubes of the power amplifier might be connected to operate in a push-pull circuit, rather than in parallel. Insofar as the plate circuit is concerned, this connection might not be advantageous. The optimum plate-to-plate load impedance for the push-pull circuit would be four times that for the parallel circuit. A center-tapped output transformer, with suitable impedance ratio, would be needed. The a-c voltage existing across the revised plate load would be twice that for the parallel circuit, so that insulation problems would be increased. The value of the tuning capacitance across the load would be reduced, however, because of the increased impedance. For equal drive in the grid circuit, the powers developed in the load with either connection would be the same.

Any advantage of the push-pull circuit would come about from effects in the control-grid circuit. Maximum plate current in the tube is governed, in part, by the maximum positive control-grid voltage that can be obtained from the driver amplifier. This maximum grid voltage is limited by the power capabilities of the driver. The peak instantaneous power that the driver must supply to a single tube is $E_g i_{cm}$, where E_g is the amplitude of the grid voltage and i_{cm} is the maximum instantaneous grid current. The average driving power is $E_g I_{g1}/2$, where I_{g1} is the fundamental component of grid current. Since i_{cm} is many times I_{g1}, the peak driving power is many times the average driving power.

If two tubes are operated in parallel, both i_{cm} and I_{g1} will have twice the values for a single tube, and the ratio between peak and average driving power is unchanged from that for a single tube. If two tubes are operated in push-pull, I_{g1} is twice that for a single tube, but i_{cm} has the same value as for a single tube. This constancy of i_{cm} comes about because the two tubes of the push-pull circuit operate on alternate half cycles, and only one grid draws current at a time. As a result, the peak driving power for a push-pull connection is the same as for a single tube, while the average driving power is doubled.

The maximum instantaneous positive control-grid voltage that can be developed often is limited by the required peak driving power, for the customary design of a driver amplifier. Thus, the implication of the foregoing discussion is that for a given driver amplifier of typical design, a higher a-c grid voltage possibly can be obtained with a push-pull connection than with a parallel connection of the power amplifier. The increased grid drive is useful only if voltage and dissipation ratings in the grid circuit are not exceeded. In any case, a special push-pull driver transformer is required.

With any design for the power amplifier, the magnitude Z_b of the plate load impedance should be large enough that the a-c voltage across it approaches in value the plate supply voltage. This choice of Z_b is dependent upon the choice of operating voltages for the tubes. For the amplifier as used in the experiments, with the maximum obtainable grid driving voltage, the optimum load impedance is in the order of

500 ohms, as seen from Fig. 13. In any case, it obviously is desirable to have the angle θ of the load impedance as small as possible.

Pulsed operation brings in the additional consideration of the shape of the envelope of the pulse. The envelope should rise and fall smoothly, without overshoots or ringing. Overshoots give excessive voltages which may cause insulation breakdowns in the system. Ringing effects, in general, represent a spread of energy into frequency bands where it is not desired. A smooth envelope on the pulse coming out of the amplifier requires a smooth envelope on the pulse applied to its grid. In addition, the load impedance of the amplifier should have a single maximum at the carrier frequency, and should drop smoothly at other frequencies. Any sharp peaks on the impedance curve, at other than the carrier frequency, will lead to ringing effects. A load impedance involving the interconnection of a number of resonant elements is almost certain to show undesirable variations in impedance, unless it has been carefully designed.

Appendix A. Envelope of Response of Pulsed Amplifier

The instantaneous plate current of a Class-C amplifier consists of a sequence of short pulses. Their repetition frequency is the frequency of the carrier driving the amplifier, and the shape of an individual pulse depends upon the adjustment of the amplifier. These pulses of current are applied to some sort of tuned load circuit. The impedance of this load normally is chosen to be high at the carrier frequency and low at other frequencies. As a result, the load acts as a filter and the voltage appearing across it (i.e. the a-c plate voltage of the amplifier) is essentially sinusoidal. Filtering action is improved, and the voltage is more nearly sinusoidal for a load that is more sharply tuned or that has a higher circuit Q. The voltage appearing across the load can be found by resolving the plate-current pulses into their Fourier components. The products of each component of current and the impedance of the load at the frequency of that component give the components of voltage. The sum of the component voltages is the total voltage across the load.

If the amplifier is subjected to pulsed operation, the train of plate-current pulses is turned off and on. The a-c voltage across the load builds up and decays in accordance with the changes in current. If the impedance of the load has a sharp maximum at the carrier frequency of the current pulses, the envelope of the voltage across the load will change smoothly as it builds up and decays. However, if the impedance maximum of the load occurs at a frequency different from the carrier frequency, as may occur with certain operational requirements, the envelope of the voltage across the load may show the phenomenon of ringing. Oscillation of the envelope takes place, with resulting over-shoots in the amplitude of the voltage, beyond its steady-state value.

A mathematical analysis of this effect is reasonably complicated because of the large number of parameters that must appear in the discussion. A simpler situation, formally quite similar to that described above, is the following. A low-pass system excited by a d-c signal has a response analogous to the envelope of the response of a band-pass system excited by a corresponding a-c signal.[1] For a qualitative discussion, it is sufficient to consider a low-pass system excited by a d-c step function.

A circuit that is simple to analyze, but which illustrates the phenomena involved, is shown in Fig. A.1. It consists of an inductance L, a capacitance C, and a conductance G, connected in parallel. A current i is supplied to this parallel combination, and as a result a magnetic flux ϕ appears in the inductor. This flux is taken as the total flux linkage, so that the voltage appearing across the inductor is merely the time derivative of ϕ.

If the current supplied to the circuit varies sinusoidally with time, as $i = I \sin \omega t$ with amplitude I, the amplitude Φ of the resulting flux is given as a function of the angular frequency ω by the equation

$$\Phi/LI = \left[(2\alpha\omega/\omega_o^2)^2 + (\omega^2/\omega_o^2 - 1)^2\right]^{-1/2}$$

where $\alpha = G/2C$ and $\omega_o^2 = 1/LC$. The quantities Φ and ω are plotted as normalized ratios to give a family of steady-state response curves in Fig. A.2, with the parameter being the circuit Q. For this circuit, $Q = C\omega_o/G = \omega_o/2\alpha$. If Q is somewhat greater than unity, the response shows a maximum near $\omega = \omega_o$; if Q is somewhat less than unity, a maximum occurs at $\omega = 0$.

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1. E. C. Cherry, J. I. E. E., 92, III, 183, (1945)

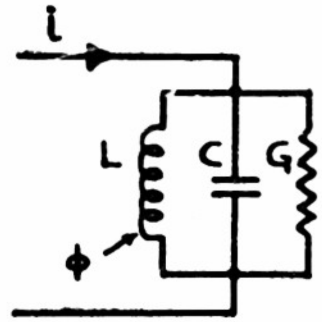

Fig. A.1. Parallel circuit

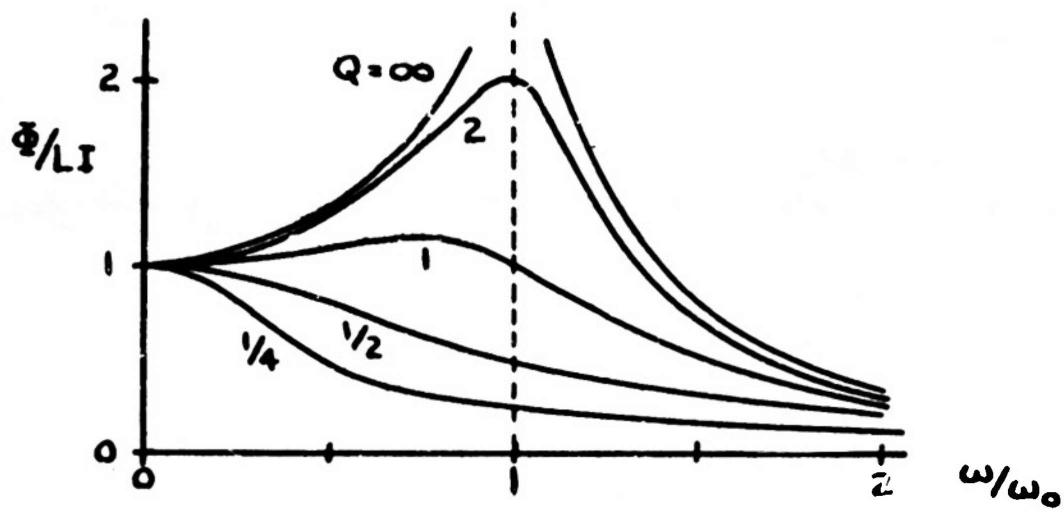

Fig. A.2. Response of circuit to sinusoid

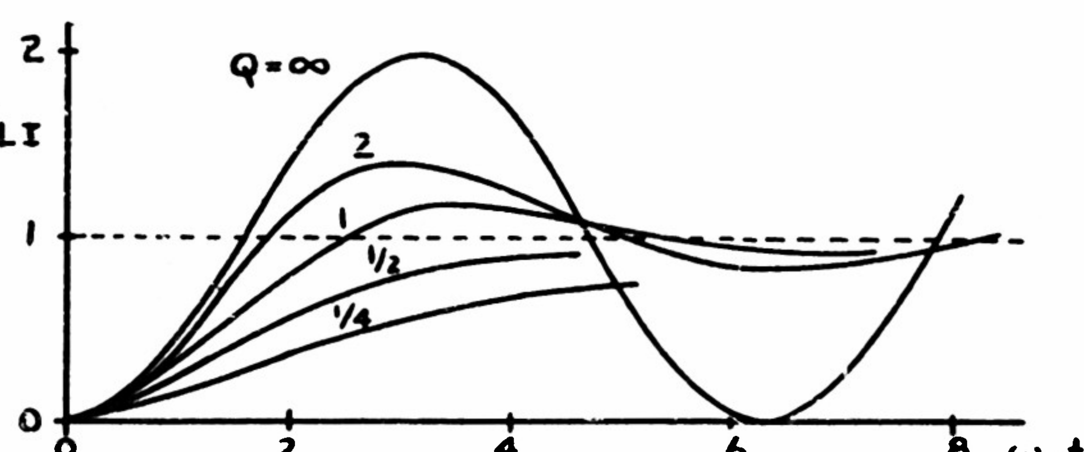

Fig. A.3. Response of circuit to step function

If the current supplied to the circuit is a step function, as $i = 0$ for $t < 0$, and $i = I$ for $t > 0$, the resulting instantaneous flux, for $t > 0$, is given by the equation

$$\phi/LI = 1 - \exp(-\alpha t)\left[\cos \omega_1 t + (\alpha/\omega_1) \sin \omega_1 t\right]$$

where $\omega_1^2 = \omega_o^2 - \alpha^2$. Initial conditions of $\phi = 0$, $d\phi/dt = 0$, at $t = 0$, are assumed. The quantities ϕ and t are plotted in normalized form in Fig. A.3 to give a family of transient response curves, with the parameter again being the circuit Q. Ultimately the ratio ϕ/LI always approaches unity. For large Q, oscillation occurs about this ultimate value; for small Q, the ultimate value is approached monotonically.

The case of small Q in the analogue of this example is equivalent to the case of the pulsed amplifier with the maximum impedance of its load circuit occurring at the carrier frequency. The maximum steady-state response for the analogue with small Q is at zero frequency, the frequency of the direct current of its exciting step function. For this situation, the transient response approaches its ultimate value monotonically; the envelope of the response of the pulsed amplifier shows no oscillation.

The case of large Q in the analogue is equivalent to the case of the amplifier with the maximum impedance of its load occurring at other than the carrier frequency. The maximum steady-state response for the analogue with large Q is at the frequency $\omega = \omega_o$, different from the zero frequency of the exciting step function. For this condition, the transient response shows oscillations which may have an instantaneous value approaching twice the ultimate value; the envelope of the response of the pulsed amplifier shows ringing with overshoot.[2]

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2. E. C. Cherry, J. I. E. E., 89, III, 19, (1942)

The amount of ringing which occurs in the pulsed amplifier will be greater for a load impedance that is more sharply tuned, or for a driving pulse having an envelope that changes more abruptly.

Appendix B. Correction of Output Power

It has been assumed in the analysis that the plate current of a tetrode or pentode is independent of plate voltage, so long as certain restrictions on the magnitude of the minimum instantaneous plate voltage are observed. While this represents a good approximation for many types of tubes, for other tubes the approximation is poor. It is desirable to make an estimate of the error involved.

There are two major effects to be considered. First, angle ϕ between the alternating grid voltage and the negative of the alternating plate voltage may not be the same as angle θ of the plate load impedance. If this is so, output power cannot be found in terms of angle θ alone. Second, there is the direct effect of plate voltage on the magnitude of plate current.

It has been shown that[1]

$$E_p/\mu_{1p}E_g = \sin(\theta - \phi)/\sin\theta$$

and that ϕ differs from θ by a larger amount as θ becomes larger. As an example, the case of θ = 60 degrees is considered, which is about as bad an operational condition as is likely to exist. Further, it is assumed arbitrarily that the maximum permissable difference between θ and ϕ is 5 degrees. Then, the ratio $E_p/\mu_{1p}E_g$ must not exceed $\sin 5^\circ/\sin 60^\circ = 0.1$. If E_{bb} is much greater than E_{c2}, as is typical in high-power amplifiers, and if the magnitude of the load impedance is adjusted for maximum power output, the peak alternating plate voltage is almost as large as the d-c plate supply voltage, $E_p \triangleq E_{bb}$. Under these assumptions, the curves of Fig. B.1 are applicable. The combination of

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1. Ref. 1, Report No. 1. The analysis there is for triodes, but the equation applies to tetrodes and pentodes also.

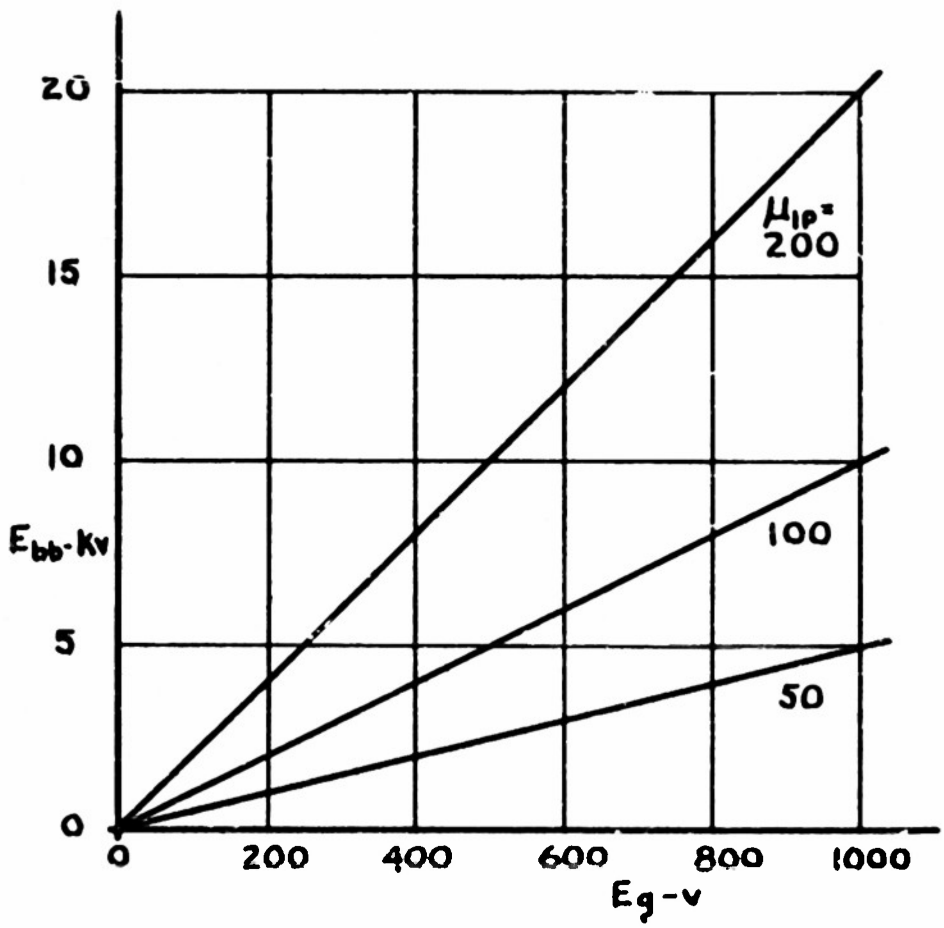

Fig. B.1. Criterion to assure $(\theta - \phi) < 5°$ for $\theta = 60°$, $\mu_{1p} E_g > 10 E_{bb}$

E_{bb} and E_g used in the amplifier must be below the line corresponding to factor μ_{1p} of the tube, if the difference between angles θ and ϕ is to be less than 5 degrees when θ = 60 degrees. Similar curves may be easily calculated for other values of θ. The curves are all shifted upward if θ is reduced, so the difference between θ and ϕ becomes smaller. It should be noted that this criterion gives a pessimistic answer, since E_p is actually somewhat smaller than E_{bb}.

In the experimental amplifier from the Type XQHB sonar, typical values are E_{bb} = 3000 volts and E_g = 500 volts. Factor μ_{1p} for the Type 5D21 tube is over 200. From Fig. A.4 it is apparent that the difference between θ and ϕ is small for this amplifier.

The instantaneous plate current in a tetrode or pentode is given by the equation

$$i_b = G'(e_{c1} + E_{c2}/\mu_{12} + e_b/\mu_{1p})^{\beta}.$$

In the simplified analysis the term e_b/μ_{1p} is considered to be zero. The other constants are evaluated with $e_b = E_{bb}$. In effect, the constants absorb the term E_{bb}/μ_{1p}, so that the implicit assumption that $e_b = E_{bb}$ is made thereafter. Thus, in operation where e_b may become small, the actual current is less than that calculated. For $\theta = \phi = 0$, the assumed peak plate current is

$$(i_{bm})_1 = G'(e_{cm} + E_{c2}/\mu_{12})^{\beta}$$

in the analysis upon which the design charts are based. However, the true plate current is less, since now $e_b = e_{bm}$ rather than $e_b = E_{bb}$. The change is $E_{bb} - e_{bm} = E_p$, so the actual peak plate current may be approximated by

$$(i_{bm})_2 = G'(e_{cm} + E_{c2}/\mu_{12} - E_p/\mu_{1p})^{\beta}$$

If it is assumed that the effect upon I_{p1}, and thus on power output at constant load impedance, is the same as on the peak plate current i_{bm} (this implies constant waveform), a correction factor for the output power may be given by the ratio

$$\left[\frac{(i_{bm})_2}{(i_{bm})_1}\right]^2 = \left[\frac{e_{cm} + E_{c2}/\mu_{12} - E_p/\mu_{1p}}{e_{cm} + E_{c2}/\mu_{12}}\right]^{2\beta}$$

For typical operation of the Type 5D21 tubes in the XQHB amplifier, with $e_{cm} = 200$ volts and $E_p = 2400$ volts, the power correction factor is

$$\left[\frac{200 + 380/7 - 2400/220}{200 + 380/7}\right]^{2.6} = 0.9.$$

The power estimated from the simple analysis should be reduced by about 10 percent. If $\theta = \phi$ is not zero, the reduction will be smaller since then e_{bm} does not occur at the same instant as i_{bm}.